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Towards a knowledge management framework for initial stages of product development processes

Dissertation

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DISSERTATION

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by

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DISSERTATION

Zu einem Wissensmanagement Framework für die frühen Phasen des Produktentwicklungsprozesses

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines
Doktors der technischen Wissenschaften (Dr. techn.)

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Statutory Declaration

I declare on oath that this dissertation was carried out and written independently by myself in accordance with the recognized principles of academic writing. All resources used, in particular the underlying literature, are named and listed in this dissertation. The text passages taken verbatim from the sources are marked as such.

The topic of this dissertation has not been submitted by me in any form as an examination paper to an assessor elsewhere. This thesis is identical to the thesis assessed by the reviewers.

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Abstract

To keep an advantage in the fiercely competitive business world of today, innovative and high-quality products must be released. Due to the high degree of technological specialization, globalization and the resulting increase in complexity, development companies must make more sound and precise decisions than in the past while driving faster innovation, particularly in product development. However, companies have to consider multiple Design for X (DfX) aspects such as usability, safety, quality, manufacturing, assembly, ergonomics, environments, cost and recycling when developing a technological product and many variants. Since this knowledge from different areas must be made available to the developers during decision-making processes, it is necessary to produce a solution that can implement DfX principles in the early design phases so that knowledge transparency and knowledge sharing can be achieved within the company to significantly improve the competitiveness of the company. Furthermore, integrating the knowledge of subject matter experts is difficult when product development teams are spread across the world. Therefore, this thesis aims to create a communication and knowledge management approach for early design stages.

This project focuses on the importance of sustainable product development by integration a knowledge management approach regarding DfX aspects in a communication platform to support development teams communicate more effectively and access the most up-to-date knowledge throughout the development process. The study therefore reviews various methods, tools and technologies based on DfX, knowledge management and communication from a product development perspective.

A systematic concept for capturing and integrating explicit and tacit knowledge related to DfX principles and guidelines is defined and presented. Moreover, this work underscores acquiring implicit knowledge from experts in various disciplines according to DfX principles that can be later retrieved and applied to shorten the duration of knowledge integration and search operations in next development processes. By integrating the hierarchical structure of the DfX with the engineering requirements, context-based knowledge retrieval can be achieved. A knowledge management methodology is proposed to acquire, store, transfer and use of knowledge. Furthermore, this work proposes a system to organize, retrieve and access knowledge by means of keywords extraction and tagging based on Natural Language Processing (NLP) to speed up decision-making.

In the section on prototypical implementation, the intended concept is described using a scenario with a use case for developing a 3D printer. In addition, the core software requirements and functions of the communication and knowledge management platform are presented. Furthermore, an application of the prototype in relation to a 3D printer is performed to summarize the results and key findings. Finally, the development potential of the implemented solution for future research is discussed in order to improve basic knowledge processes, such as capturing, storing and distributing knowledge, and also to improve communication technologies in terms of performance and knowledge sharing.

Kurzfassung

Im heutigen wettbewerbsintensiven Geschäftsumfeld ist die Einführung innovativer und qualitativ hochwertiger Produkte entscheidend, um einen Wettbewerbsvorteil zu erhalten. Aufgrund des hohen Grades an technologischer Spezialisierung und Globalisierung und der daraus resultierenden zunehmenden Komplexität müssen Entwicklungsunternehmen insbesondere in der Produktentwicklung fundiertere und präzisere Entscheidungen als in der Vergangenheit treffen und gleichzeitig die Innovation vorantreiben. Bei der Entwicklung eines technologischen Produktes und vieler Varianten müssen Unternehmen jedoch eine Vielzahl von Design for X (DfX)-Aspekten wie Gebrauchstauglichkeit, Sicherheit, Qualität, Fertigung, Montage, Ergonomie, Umwelt, Kosten und Recycling berücksichtigen. Da dieses Wissen aus verschiedenen Bereichen dem Entwickler bei der Entscheidungsfindung zur Verfügung gestellt werden muss, ist eine Lösung notwendig die DfX-Prinzipien in den frühen Entwicklungsphasen umzusetzen. Dadurch kann ein Wissenstransfer und Wissensaustausch innerhalb des Unternehmens erreicht werden, um die Wettbewerbsfähigkeit des Unternehmens deutlich zu verbessern. Darüber hinaus ist die Integration des Wissens von Fachexperten schwierig, wenn die Produktentwicklungsteams über die ganze Welt verteilt sind. Das Hauptziel dieses Projektes ist es, eine Kommunikations- und Wissensmanagementtechnik zu entwickeln, die in den frühen Entwicklungsphasen hilfreich sein wird.

Diese Forschung konzentriert sich auf die Bedeutung einer nachhaltigen Produktentwicklung durch die Kombination eines DfX-basierten Wissensmanagementsystems und einer Kommunikationsplattform, um Entwicklungsteams dabei zu unterstützen, effektiver zu kommunizieren und während des gesamten Entwicklungsprozesses auf das aktuelle Wissen zuzugreifen. Die Studie untersucht daher verschiedene Methoden, Werkzeuge und Technologien, die auf DfX, Wissensmanagement und Kommunikation aus der Sicht der Produktentwicklung basieren.

Es wird ein systematisches Konzept zur Erfassung und Integration von explizitem und implizitem Wissen in Bezug auf DfX-Prinzipien und -Richtlinien definiert und vorgestellt. Darüber hinaus unterstreicht diese Arbeit die Gewinnung von implizitem Wissen von Experten verschiedener Disziplinen auf der Grundlage von DfX-Aspekten, dass später abgerufen und genutzt werden kann, um den Zeitaufwand für die Wissenssuche und -implementierung in zukünftigen Entwicklungsprozessen zu reduzieren. Durch die Integration der hierarchischen Struktur des DfX mit den technischen Anforderungen kann eine kontextbasierte Wissensabfrage erreicht werden. Es wird eine Wissensmanagement-Methodik für den Erwerb, die Speicherung, den Transfer und die Nutzung von Wissen vorgeschlagen. Darüber hinaus wird in dieser Arbeit ein System zum Organisieren, Abrufen und Zugreifen auf Wissen durch die Verwendung von Schlüsselwörtern und Tagging auf der Basis von Natural Language Processing (NLP) vorgeschlagen, um die Entscheidungsfindung zu beschleunigen.

Im Abschnitt zur prototypischen Umsetzung wird das geplante Konzept anhand eines Szenarios mit einem Anwendungsfall zur Entwicklung eines 3D-Druckers beschrieben. Darüber hinaus werden die wesentlichen Softwareanforderungen und Funktionen der Kommunikations- und Wissensmanagementplattform zusammengefasst und vorgestellt. Weiterhin wird eine

Anwendung des Prototyps in Bezug auf einen 3D-Drucker durchgeführt, um die Ergebnisse und wichtigsten Erkenntnisse zu bestimmen. Abschließend wird das Entwicklungspotenzial der implementierten Lösung für die zukünftige Forschung diskutiert, um grundlegende Wissensprozesse, wie die Erfassung, Speicherung und Verteilung von Wissen, sowie die Kommunikationstechnologien in Bezug auf Leistung und Wissensaustausch zu verbessern.

Contents

List of Abbreviations

API	Application Programming Interface
AR	Augmented Reality
BOM	Bill of Materials
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAx	Computer-Aided Technologies
CRM	Customer Relationship Management
CSCW	Computer-Supported Cooperative Work
DB	Database
DfA	Design for Assembly
DfC	Design for Cost
DfE	Design for Environment
DfM	Design for Manufacturability
DfQ	Design for Quality
DfR	Design for Reliability
DfV	Design for Variability
DfX	Design for Excellence
DM	Data Mining
DMS	Document Management Systems
DMU	Digital Mock-Up
EMS	Electronic Meeting Systems
ERP	Enterprise Resource Planning
FDM	Fused Deposition Modeling
FEM	Finite Element Modeling
FMEA	Failure Mode and Effects Analysis
FTA	The Fault Tree Analysis
HTML	Hypertext Markup Language

IT	Information Technology
JSF	Java Server Faces
KBE	Knowledge-Based Engineering
KM	Knowledge Management
KMS	Knowledge Management Systems
KNOMAD	Knowledge Nurture for Optimal Multidisciplinary Analysis and Design
ML	Machine Learning
MML	Moka Modelling Language
MOKA	Methodologies and Tools Oriented to Knowledge-Based Engineering Applications
MVC	Model-View-Controller
NLP	Natural Language Processing
OCR	Optical Character Recognition
PD	Product Development
PHP	Hypertext Pre-Processor
QFD	Quality Function Deployment
TOM	Technology, Organization and People
TRIZ	Theory of Inventive Problem Solving
UI	User Interface
UML	Universal Modeling Language
URL	Uniform Resource Locator
VDI	Verein Deutscher Ingenieur
VR	Virtual Reality
WWW	World Wide Web

1 Introduction

1.1 Motivation

In today's highly competitive industrial and productive sector, the market launch of innovative and high-quality products becomes a primary factor for improving a company's competitive position especially in engineering products. The achievement of this success depends on bringing innovative ideas and products to market for a brief time. Design process has higher importance to shorten the time in the entire product development process, particularly for the creating novel products. A design process's primary goal is to develop the highest quality product to satisfy specific customer demands. However, rapidly changing customer needs and technologies are leading to complex products in the form of diversity or variability [Masior et al., 2020]. A productive design approach is required to achieve these criteria. Definition of requirements, conceptual design, embodiment design, detailed design and production usually set up a design process [Mejía-Gutiérrez, 2011]. Numerous factors, including such as assembly, safety, environment, manufacturing and quality, must be brought into consideration during these stages [Faerber, 2008]. Moreover, a series of activities that link experts and information have to be applied in a systematic development process [Clarkson, 2005]. In the design phase various choices and decisions are taken which have impact on the other development phases and these decisions are highly knowledge and experience driven [Bricogne, 2010].

Nowadays product design often takes place in a global environment in distributed teams, and product development teams have to provide more accurate products in a brief period of time. It is vital to integrate the knowledge and expertise of specialists at the initial stages of product development since identifying and collaboratively designing a product is a knowledge-intensive process. However, members of the design team are already busy at the conceptual stage, and designers lack the time to establish the product's knowledge base. As a result, obtaining and reusing expertise related design throughout the product development process becomes a top priority [Zhong, 2005]. One of the key criteria for success is the application of knowledge and connecting it to the designer's creativity and ability. Finding appropriate information to help decision-making is challenging due to the growing amount of information that development teams and designers must take into account. Participants within the design team need to consider and use appropriate knowledge everywhere in the product development. The increasing globalization of the manufacturing industry forces companies to utilize all available knowledge. However, visibility and availability of knowledge is not simple. When developing a product, using and giving the appropriate knowledge, such as information, principles and rules, at the earliest opportunity becomes crucial for the designers to make the right choices on time [Guera, 2002] [Vajna, 2002]. In real world applications, different types of knowledge have to interact in a collaborative design process, designers must implement an early and continuous assessment of fundamental criteria, rules, or expertise from several fields for a product's cost, quality and environmental attributes [Stoeber, 2009].

Knowledge has recently emerged as a crucial production element as a result of greater product complexity, which causes a sharp increase in knowledge demand across the whole industrial production process [Langenberg, 2001]. Design engineers need to apply different information and know-how, which have to be delivered from the best source and at the right time. In design, domain specific knowledge of different disciplines, for example, the possibilities of specific materials to fulfil certain concept solutions or existing knowledge for environmentally sustainable design solutions, can be in form documented and shared knowledge within a design team [Christiaans, 2005]. The information gained throughout product development is crucial for achieving a good outcome for the design of a high-quality product. Not only design decision knowledge such as design revision, design standard, production and experiences from past design projects, but also process knowledge in a technology-oriented innovating environment have to be considered, which may refer to specific technologies, their capabilities and performance, understanding of process planning, knowledge of labor and resource availability [Malins, 2014] [Zhong, 2005]. In addition, the rapidly increasing complexity is becoming a major problem, especially for inexperienced engineers, particularly in the development of mechatronic products [Heimicke et al., 2019].

To be a successful company in product design not only to be able to create and acquire knowledge but also the gained knowledge has to be disseminated and represented rapidly into the development team. During the last decades, many technologies have been developed, which provide the knowledge to improve product development decisions therefore knowledge has expanded. As a result of this improvement, updating of the knowledge holds an important place to obtain a competitive advantage for the industry [Guera, 2002]. Main challenge is transfer and effectively use of acquired knowledge into new product development [Gao, 2017]. Product design is a dynamic process therefore, it is critical to create successful knowledge accessibility and effective sharing of information in organizations to prevent repetition and duplication of effort [Ugurlu & Gerhard, 2017]. How to efficiently acquire and represent knowledge, at the same time, knowledge have to be structured and stored in order to update and improve. It is possible to extract design information and use it while creating new products. These are all significant factors in enhancing the performance of development processes in relation to the knowledge, therefore, the management of expert- and development knowledge has effectively solidly established as a field to collect, distribute and increase information inside the organization.

Early on in the process of developing a product, for example, conceptual product design is an essential area which is heavily influenced by each individual's experiences, innovative thinking and tacit knowledge [De Araujo, 2001]. Therefore, the access to existing expert and development knowledge in addition to already acquired and stored information is of crucial importance for the creation of products and their design [Breitsprecher, 2011]. However, implicit design knowledge is very difficult to exchange especially in distributed design teams. The engineering design process is a multidisciplinary and cooperative activity, and many specialized tasks have to be accomplished according to information and feedback from other areas of specialization. Therefore, the success of multidisciplinary design process relies on communication and sharing information into the engineering design team. If the lack of communication and ineffective collaboration during the product development reaches a critical level, which may be costly in terms of time and money [Malins, 2014]. Furthermore, the limited and non-goal-oriented communication is one of the biggest problems for the loss of implicit knowledge of experts, which has its roots in activity and participation in a particular area. On the other side if reuse of existing knowledge is provided into multidisciplinary design team, which work concurrently and communicate effectively, for the next product development activities, new information may be created and integrated into the knowledge management cycle [Bricogne, 2010]. For the solution of mentioned problems new technologies are required. These technologies may provide, on the one hand, the accomplishment of beneficial information exchange and accessibility across product development teams, on the other hand, support acquiring, dissemination and sharing of design expertise within the design team.

According to the latest studies, new digital technologies have proved essential for managing knowledge in the processes of product creation. These include, but are not restricted to, machine learning and data analytics, all of which have made substantial advancements in the managing, understanding and using of data [Chopra et al., 2021] [Manesh et al., 2020]. For instance, machine learning (ML) and data analytics can help predict patterns and trends, enabling product developers to be more proactive and efficient in decision-making processes [Dogan & Birant, 2021]. A sample graph showing how the studies on these subjects have increased in recent years is shown in Figure 1. With the help of these technologies, effective reusing of the knowledge that is already present inside a business, improvement of performing at work and coming up with innovative ideas in development teams may be possible [Gao, 2017].

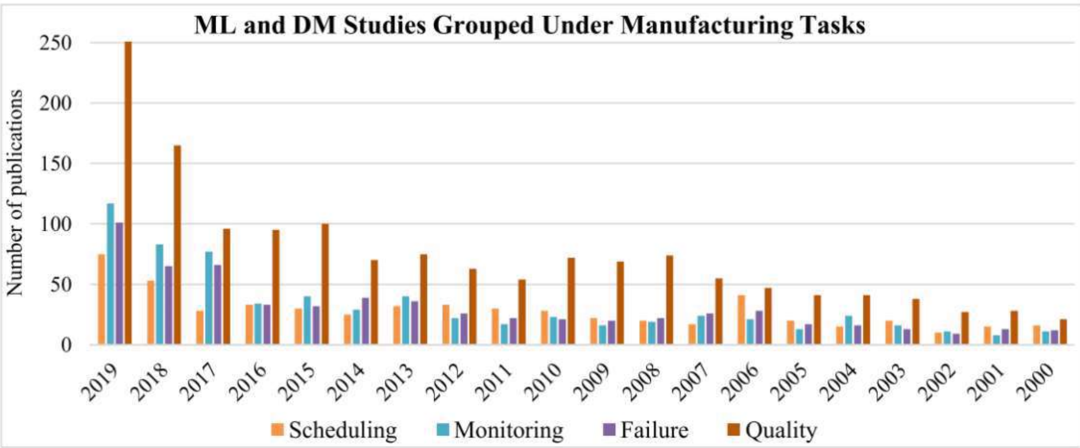

Figure 1, The number of publications culled from Scopus between 2000 and 2019 in accordance with their goals [Dogan & Birant, 2021]

Based on this technological development, the explosion of industrial big data on sensors, equipment logs, and operational records has provided an enormous revolution in manufacturing and management through the application of intelligent systems to decision-making [Gandhi et al., 2018]. Instead of being passive databases of information, decision support systems become active advisors that continuously analyze data streams, detect deviations and make recommendations appropriate to the situation, and facilitate data-centric decision making [Confalonieri et al., 2015]. Furthermore, data mining enables the creation of models of prediction which may forecast crucial design metrics, pinpoint the best production processes and identify flaws in earlier designs [Kusiak & Tseng, 2000]. As discussed by Chien et al. [2007], employing algorithms like neural networks, neural decision trees and grouping to explore knowledge of historical design norms might offer insightful information on the interdependence between product features, process variables and efficiency parameters [Chien et al., 2007]. Data Mining (DM) makes it easier to analyze the parallels between current items to create a perfect framework from the perspective of a product line [Agard & Kusiak, 2004].

A successful product requires the designer to make the best decisions as early as feasible. However, a product always based on knowledge therefore linking of needed information is very important for the designer in the product development processes. The information relating to Design for X from other areas of product life cycle, e.g., product behavior, price, cost-effective production techniques, implications, functions and limitations etc., have to be provided on time [Vajna, 2002]. Design for X is indeed a knowledge system that supports product development decision-making; therefore, developers are able to reach various context-based information. Information from different areas, e.g., usability, safety, quality, manufacturing, assembly, ergonomics, environments, cost and recycling, provides a continuous improvement and problem-solving ability to minimize cost and waste in the product development. The success of a goal-oriented linking and collection of knowledge from other fields may be influenced by the application of DfX methodologies, tools and approaches. On the one hand, being able to incorporate DfX-based knowledge into the method of innovation may have significant implications for decision making, on the other hand, is a competitive advantage to fulfil and achieve requirements of a product, e.g., increased quality, added functionality and speed of innovation [Ringen, 2016]. There is a growing emphasis on the holistic approach in product design, which entails the consideration of all these aspects right into the initial design stages [Benabdellah et al., 2021].

Furthermore, developed technologies enable a rapid knowledge transfer during the design process by using e.g., artificial intelligence techniques, moreover, information may be maintained in computerized systems in a number of formats, including documents (text), photos, diagrams and rules [De Araújo, 2001] [Baxter, 2007]. Due to these improvements, knowledge is becoming a very important factor and advantage for the special manufacturing companies, therefore development new technologies are necessary, for instance, a system that enables the explicit transfer of implicit knowledge and the sharing of this information across concurrent engineering team members during the design process [Mejía-Gutiérrez, 2011].

The primary research issue addressed by the current thesis is whether there can be a process-model so that the previously addressed problems and key points can be effectively solved. In addition, the following subordinate questions arise to define main goals and concept of this work also as shown in Figure 2:

How should a process-model be built to assist development team in the initial phases of development for decision-making process?

How systematically the experts' tacit knowledge and experiences can be goal oriented acquired from various areas in the product development process and transferred into an explicit form?

Which methods should have this process-model therefore the acquired domain specific knowledge can be made available or visualized to the developer at the appropriate time and quantity?

Which aspects and requirements must include the process-model, on the one hand, in order to improve knowledge transparency and effective knowledge sharing across distributed design teams, on the other hand, to provide effective use of acquired knowledge?

The primary objective of this work is to generate a concept to advance the development teams in early design stages through a DfX-based knowledge management and communication platform. The aim is to assist decision processes through reuse previous knowledge from completed projects to make it possible to generate reliable designs rapidly and economically. This concept focused on managing the gathering and connecting of acquired knowledge through keywords extraction method according to DfX principles. Furthermore, this approach aims knowledge transparency and effective knowledge sharing to create a dynamic framework through ongoing knowledge improvement. Moreover, a key advantage of this system is the structured acquisition and storage of implicit professional technical product know-how. This concept enables representation of design purpose and specific knowledge of the subject while the development team collaborates and communicates. As a result, this new strategy can give the appropriate engineering knowledge to the appropriate individuals at a suitable time.

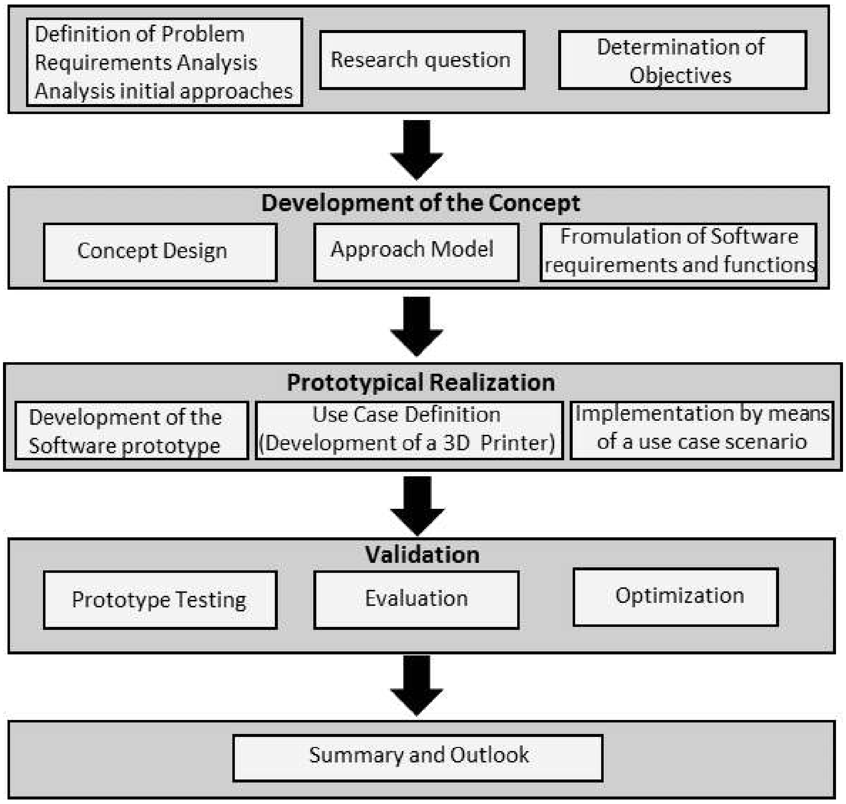

Figure 2, Research plan

2 Product Development

Product development as a business process and organizational unit convert customer needs into technical and commercial solutions such as product and service [Ferreira et al., 2007]. As individuals or in teams, developers generate concepts and design solutions for innovative products. In order to develop a product of exceptional quality there are a large number of influencing factors from various areas and these elements must be considered throughout the product development process. These factors may be external influences such as competition, suppliers, customer and environment. Others may contain, for example, the available resources, using technologies, processes, type of product, and moreover, methods and tools used in the knowledge management [Ponn, 2011] [Lindemann, 2009].

Early development work preparation is the first step in designing and developing successful products. After planning a product, many activities of the initial phases of the innovation process are very important to define the essential characteristics of a future product. In this stage developers need different kinds of knowledge and information, for example, a challenging integration of information is required from, quality, sales, engineering, manufacturing and supplier [Morgan & Liker, 2020]. This information must be provided so that the developer can make best decision for a technical problem in the further processes on the basis of the existing product concepts. Therefore, the best solution can efficiently implement planned concepts into successful products [Seidel, 2005]. Solving a design problem is a knowledge intensive process especially in early stages of product development and it usually consists of five steps:

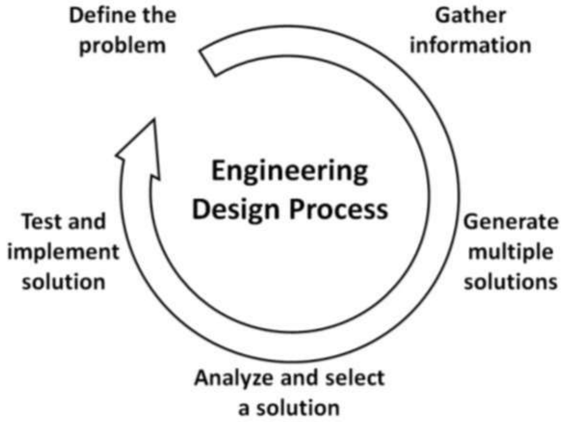

Figure 3, Solving a design problem [Khandani, 2005]

The first step (in Figure 3), problem description, includes product or client conditions and specially information about product functions. In the following step, relevant information and functional specifications for the design of the product are gathered. After finishing the detail design, developer create multiple solutions according to inputs from other areas, for example, manufacturing or marketing. In the next step, more acceptable alternatives are selected and available solutions regarding to cost, safety and other criteria are analyzed since the final design of product may be provided and identified that fulfil the requirements. As the last phase, a prototype of the created design is generated, and functional tests are performed. However, in Figure 3 represented nonstop iterative process is executed in order to induce different results, if the result doesn't work [Khandani, 2005].

In the following section first of all the process for product development is outlined in details and mainly new product development is focused on this section from a knowledge perspective. Moreover, some methods and tools to support development team are examined from the standpoint of knowledge. Besides, DfX is explained to understand categorizing knowledge and information according to DfX aspects. Product and Process knowledge is also summarized in this section to get a first understanding of the type of knowledge in a company which will be defined and discussed in detail in the next chapter. This work's primary objective is to develop a new knowledge management and communication platform, so that, Knowledge Based Engineering is also discussed shortly to show and understand how this concept distinguishes from KBE. As a result, all these topics will be discussed in relation to the planned concept.

2.1 Product Development Processes

It is noticeable that there are too many different product development processes to be able to describe just one. Therefore, a number of process models have developed, which differ in structure, content and focus. In this concept, the basic of the process of developing a product, which is commonly used for both academic [Pahl et al., 2006] [Catic, 2011] and industrial purposes according to VDI 2221 [VDI 1993], is described and discussed. This engineering design strategy's primary objective is to support designers with process models, methods and strategies, thus promoting a systematic product development [Pahl et al., 2006]. Because of this methodology, the knowledge perspective is used in this section to identify and explain the knowledge waste also the function of knowledge in product development.

The following primary phases constitute the product development process: Task Clarification; Conceptual Design; Embodiment Design; Detail Design and Overall Design Process.

The task clarification includes definition and creating the overall and task-specific specifications with the purpose of a requirements list. In this phase collection of information about the requirements and about the existing constraints is a significant task since a design project's success can be evaluated in the following phases.

Once the task has been clarified, the conceptual design phase outlines the primary method of action. To do this, function structures are created, the essential problems are abstracted, suitable working principles searched for, and finally the functional structure is formed by combining the working principles. Conceptual design leads to the specification of a primary solution.

In the embodiment stage, the general layout design as well as the component forms and materials must be determined by designers. Technology and production process considerations are crucial. To create the design, scale drawings, evaluations and checks of function, durability, manufacture, assembly and operation are made. Therefore, definitive design may be evaluated from a technical and economic perspective.

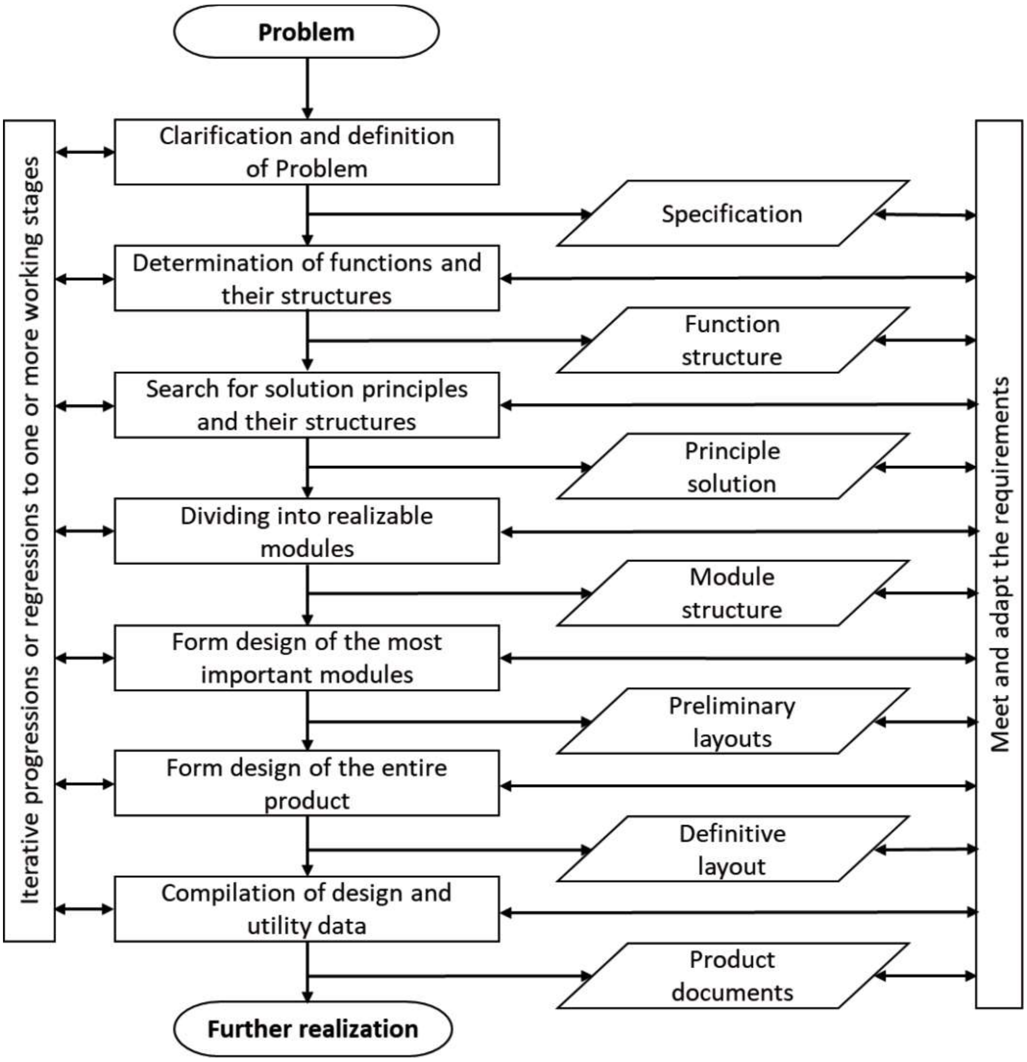

Figure 4, VDI-procedure in general for methodical development [VDI 2221, 1993]

In detail design, forms, dimensions and surface characteristics of components are finally defined. Production and costs are evaluated. All of the drawings and other production documentation are the end result of the detail design process. The following overall design process includes main themes such as optimization of principle, layout and production.

The processes explained above to generate solution for technical problems is highly depended on applying experiences and engineering knowledge of design engineers. Furthermore, optimization of provided solution within the requirements and constraints in conceptual design phase is an essential element since the product performance and its life cycle is detected. During specification, considerations in the areas such as recycling, maintainability, material and environment have to be executed. Although the knowledge management has a main role for the solution of problems, knowledge and experiences have been least documented and managed in early stages of the design [Pahl et al., 2006] [Ferreira et al., 2007].

Design engineers generally reuse knowledge implicitly related to product life cycle aspects, however, lean product development is not effectively completed due to different types of knowledge waste [McMahon et al., 2004]. These wastes may be defined as operational waste, for example, taking longer to make decisions and not having access to the appropriate information at the appropriate time. In addition, product development generates knowledge and information during the design stage. However, current methods and tools doesn't concentrate on the waste of knowledge with regard to product and process [Catic, 2011].

Providing a common knowledge base and a common understanding of terms and contexts is very important since misunderstandings and wrong specifications in teams cause mostly failure in development projects. Three essential components are described to accomplish a common understanding of work content and a working cooperation. An effective communication process at first to exchange information and knowledge in development team. Second, a coordination process between actors and activities, and third, knowledge integration process [Siau & Wang, 2007] [Steinheider & Reiband, 2002].

Based on the aforementioned information, six distinct sub-sections have been identified. By capturing, storing and disseminating knowledge, Knowledge Management Systems (KMS) help eliminate information loss while increasing the effectiveness of making decisions [Wang et al., 2017] [Martins et al., 2019]. Strategies for coding and personalizing knowledge, which involve recording knowledge and promoting direct knowledge sharing between individuals, are essential in the initial phases of product developments [Venkitachalam & Willmott, 2017]. The function of tacit knowledge, which is hard to describe and frequently acquired by means of experience, is especially valuable in the early stages when creativity and problem-solving are paramount [Ganguly et al., 2019] [Pérez-Luño et al., 2019]. The achievement of knowledge management in developing products is greatly impacted by an organization's culture, with a culture that fosters learning, sharing and collaboration in favor of knowledge management effective [Zammuto & O'Connor, 2018]. Tools like knowledge testing and mapping are useful for knowledge management in product development, helping to identify existing knowledge, location, ownership, and usage knowledge, thereby detecting gaps, redundancies and opportunities for knowledge sharing [Hutchinson et al., 2021]. Ultimately, the establishment of knowledge management metrics, which can measure aspects such as knowledge use, sharing and creation, will be beneficial in ensuring effective management of knowledge in product development [de Almeida et al., 2018].

2.2 The Value of Initial Stages of Product Development

Initial design activities are significant part to achieve a successful product since changes in late stages can be avoided in early stages, therefore, wasting time and money can be prevented. Early stages of design include mainly creation of concept, defining functions, searching suitable working principles and determination principal solutions. In this phase, amount of information is low and the generated product representations are uncertain. Therefore, a systematic and methodological approach in the early stages can decrease many expensive and time-consuming changes in late phases in product development. Some important components have been identified in consideration of this reality in order to prevent irrational decisions and errors during the initial phases of product development.

- In general, determination the most effective solution to an issue is not clear due to the low information level in early stages. Therefore, detailed clarification of requirements, systems engineering, and functional analysis can provide an improvement for low information level.

- Taking alternative solutions into account and accurate clarification of the task are essential since in most cases the first solution is chosen and developed that can cause consuming a lot of money and time as well as neglection of significant requirements.
- Consideration of existing knowledge from previous projects is not applied in many cases therefore solution catalogues and also graphical representations of the solutions such as drawings or sketches become an important part. This exiting knowledge can be used in order to provide a fast information retrieval.
- In the product development processes, various stakeholders such as provider, product designer, manufacturing engineer and technician, describe problems or solutions different points of view that causes communication problems due to the verbal description as well as different vocabulary. These problems can be simplified through working with graphical representations.
- To effectively make design changes in CAD, designers can facilitate their analysis step in a VR environment to understand the impact of the proposed changes.

Above mentioned facts have to be considered and appropriate solutions have to be engaged in the initial stages of product development to avoid undesired effects due to time and cost. In summary, development engineers have to be supported during carrying activities, for example, gathering inspirational materials and communicating concrete design ideas with suitable methods, guidelines and tools in early design [Berg & Vance, 2017] [Hughes & Jorge, 2004] [Markopoulos et al., 2016].

2.3 Methods and Technologies for Product Development

The purpose of the following part is to give a review of the techniques and resources that enable problem-solving, with a focus on those that are utilized in the initial stages of product development, for example, concept, creation, testing and evaluation. A method describes a rule-based and planned process that includes defined tasks to execute for a particular purpose. There are many particular working methods which are applied unconsciously depends on knowledge of experienced developers so that many routine tasks can be executed effectively by using knowledge of experienced developers. However, for many critical situations or problems which developers are inexperienced, diverse working methods and tools are available based on the task in development processes such as QFD (Quality Function Deployment), FMEA (Failure Mode and Effect Analysis) and TRIZ [Lindemann, 2009]. The use of these methods with different tools can be simple or complex. Checklists or design catalogues can be given as an example for simple tools, and FEM (Finite element modelling) simulation for complex tools [Ponn, 2011]. Following section summarizes and gives an overview for methods and tools which are used in product development processes. Especially methods and tools are summarized according to problem prevention, knowledge-based systems as well as problem-solving for supporting the design phase.

Early in the product development, creativity and adapting on changing requirements are main focuses, therefore, software tools are rarely in use in these stages to support tasks. For the searching and generation of ideas, creative methods like brainstorming or 635 are conceivable and applied within the early stages of product creation process. These group-based investigation methods provide collective group knowledge and synergy in order to find design solutions which can be carried out with respect to requirements or potential failure modes. However, method 635 support more individuality in addition to collective investigation therefore this technique has deeper and quieter individuals than brainstorming [Mattson & Sorensen, 2020]. Implicit knowledge of developers is not only the input to create ideas in these phases but also other sources such as lead users, competitors, research and production [Kirisci et al., 2011]. Moreover, avoiding problems is another essential issue in these stages which can be provided with various methods specified by the field of quality management. To identify failure risk and reduce it through design changes, FMEA or FTA (the fault tree analysis) are carried out. FMEA is a subjective design tool that may be executed on the product and also the process. FTA identifies potential failures in a product and also their interaction with failures in the manufacturing process or in subsystems of the products. Additionally, QFD, which provides a targeted implementation of requirements in the entire product creation process, is another method to avoid failures in advance and improve the design by using customer voice. The basic approach is the connection of different modelling levels of the product properties via matrices (House of Quality) [Mattson & Sorensen, 2020] [Wagner, 2008].

In addition to methods for avoiding problems, approaches for problem solving are also an essential part in the product development such as VDI guidelines 2221, 2222 and 2206 are commonly used basis approaches. The methodology VDI 2221 [VDI 2221], that is also thoroughly explained in section 2.1, is for designing and generating technical products and systems. The focus of this approach is on the result documents, which emerge from the individual steps within the early development stages for a product. The VDI 2222 [VDI 2222], is applied as design methodology for methodological development of solution principles. There is a description of the design procedure for mechatronic systems in VDI guideline 2206 [VDI 2206], which primarily covers the design of systems, domain-specific design, and integrating the system [Ponn, 2011] [Wagner, 2008]. Another method is the TRIZ which is applied for systematic brainstorming and development of innovative concepts. Main purposes of this method are shortening invention times and structuring problem-solving processes so that breakthrough thinking is made possible [Klein, 2014]. Furthermore, potential methods to help problem-solving include knowledge-based systems like case-based reasoning and expert systems. Reasoning is the search for solutions to a specific task by using the available knowledge that is combined and applied to achieve a solution [Gottlob et al., 1990]. Expert systems apply knowledge of experts in order to achieve or even exceed the abilities to solve issues of a human expert in a specified area [Schaffer, 1996] [Wagner, 2008].

In the design phase, many development tasks are also supported with different tools. Computer Aided Technologies (CAx) are used from functional design to detail geometric design. Computer Aided Design (CAD) is applied to provide geometric representations of parts and assembled products as well as for the preparation of technical drawings. In product and process development, CAD modelling can provide a significant simplification to complete tasks and an effective refinement especially during the concept development [Mattson & Sorensen, 2020] [Kirisci et al., 2011]. To perform testing and evaluation for the creation of complex and technical systems, tools for virtual product creation have become a key factor in the daily engineering practice. Visualization solutions such as Digital Mock-Up (DMU), Virtual Reality (VR) or Augmented Reality (AR) support decision-making processes and assembly simulations, therefore, early user feedback can be provided before real prototypes are available [Kirisci et al., 2011] [Müller et al., 2013]. Additionally, Finite element modelling (FEM) is applied as an engineering modelling to get high accurate predictions by using numerical solutions. Structural modelling, thermal modelling and fluid modelling are commonly used numerical solutions to solve problems which are complex for analytical solutions.

Effective product development relies on the application of robust methods and tools. Supplier integration frameworks acknowledge another important dimension for the interaction, people, processes and technology in enabling productive participation [Flankegard et al., 2021]. The practical utility of product development methods can be enhanced by using of supporting tools, which make application more efficient and productive [Ponn & Lindemann, 2008]. Tools encompass a range of resources from simple checklists to advanced technological systems that facilitate the use of specific techniques or provide capabilities more broadly across methods [Atzberger et al., 2020]. By aligning methods and tools is key to maximizing the results of product development processes.

Additionally, practitioners and academics have developed a number of methods and approaches to help development teams in the initial phases of the processes for the desirable product concepts [Meinel et al., 2020] [Mele & Campana, 2021]. For instance, using design for excellent (DfX) tools, program for simulation, virtual and physical prototypes, and computer-aided engineering (CAE) systems. A wide array of methods and tools exist to enhance product creation capabilities. Specifically, the interaction dimension emphasizes connections and communication with suppliers and customers during development [Meinel et al., 2020] which can significantly impact project outcome [Flankegard et al., 2021].

2.4 DfX for Product Development

In the literature, many aspects and rules defined and discussed in the development and engineering design in order to provide main objectives for a product, for example, about ergonomics, manufacturing, maintenance, standards and so on. But the reality of developing new products demands a far more pragmatic strategy that makes use of measures to guarantee that design procedures align with consumer and societal goals from inception to end of life [Benabdellah et al., 2021]. Market diversification, pricing pressure, level of complexity, a changing industrial environment, and employment costs are just a few of the numerous challenges that firms must overcome to be competitive [Benabdellah et al., 2021] [Benabdellah et al., 2018].

DfX methodologies cover all aspects of the product lifecycle, involving assembly, quality assurance, manufacturing, logistics, packaging, environmental impact, dependability and customer service. Cross-functional cooperation and concurrent engineering are necessary for effective DfX implementation in order to translate goals into sensible needs and choices during development [Benabdellah et al., 2020].

Furthermore, in most cases, the term Design for X (DfX) stands for consideration of conflicting requirements for a product which has to be developed and find the best possible adjustment between them to achieve valuable efforts in product development [Pahl et al., 2006] [Bauer, 2009]. Most common topics are the production-oriented design („Design for Manufacturing ", [Ulrich et al., 1995]), the assembly-appropriate design („Design for Assembly ", [Andreasen et al., 1988]) and the cost-effective design [Ehrlenspiel et al., 2007], which primarily have the X-compatible product design to focus [Ponn, 2011].

The effect of DfX on production advancements is now the subject of extensive experimental investigation. The majority of them draw attention to a gap in the advanced for CAD-integrated DfX methodologies as well as chances to exchange explicit engineering knowledge in the initial phases of product development. As shown in Figure 5, a horizontal level that is the same and consistent across all DfX methods makes up the suggested ontology, together with a number of vertical levels (n-levels), one for each design aim and able to express numerous design processes. Once an innovative approach is added to this structure, just the vertical layer needs to be modified to include the new concepts [Favi et al., 2022].

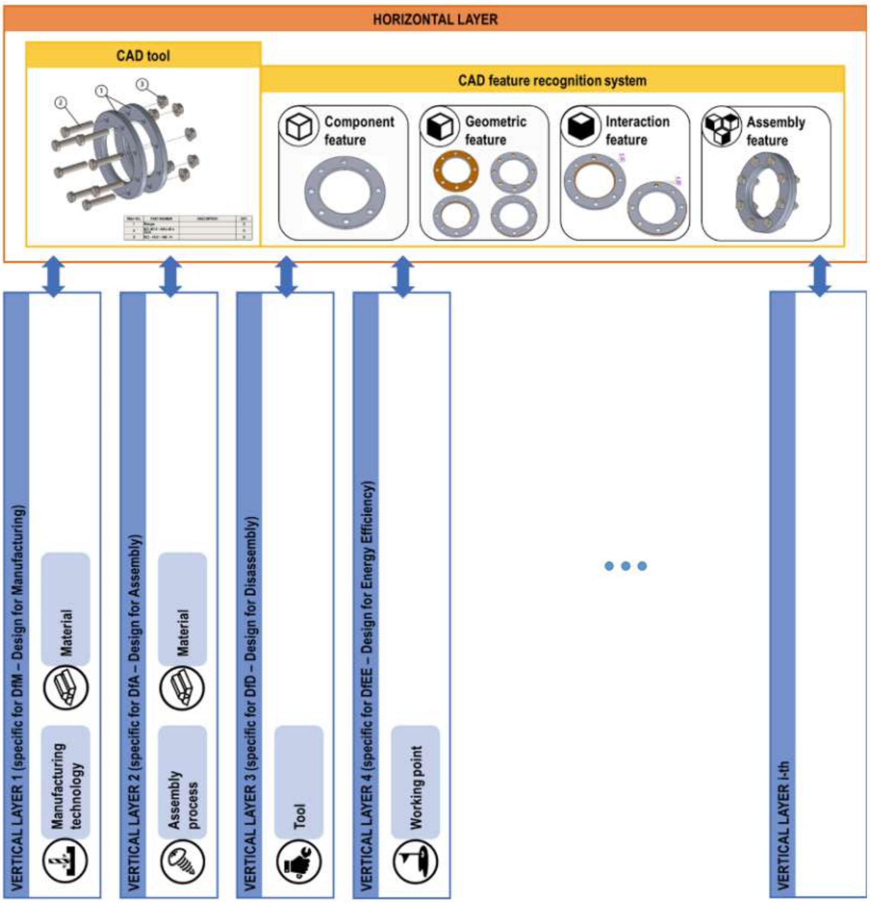

Figure 5, The DfX system's methodology is integrated with CAD [Favi et al., 2022].

DfX provides a wide range of different types of tools (design guidelines, checklists, methodologies and software tools) for suitable consideration of different disciplines, which enables finding a solution for a process and product in active use [Chiu et al., 2007] [Bauer, 2009]. Therefore, developers are supported to determine an acceptable characteristic factor suited for the desired feature by taking into account the numerous dependencies. Tools for guidelines support developers during the product development processes to point out the way to the realization of as many as possible desired properties of the product and associated processes. DfX methods are systematic approaches for the successful application of DfX guidelines, and in addition DfX tools are practical applications generally in form of software solutions for product developers, in which DfX methods are realized [Bauer, 2005] [Bauer et al., 2007] [Bauer, 2009].

DfX methods can be characterized as a codification strategy to support knowledge management in concurrent engineering [Huang, 1996]. However, due to the needs of a particular company, this is considerably behind the creation of an explicit knowledge management plan, for example, assigned activities, roles and methods are necessary for a knowledge management system in an organization [Catic, 2011]. Product designers need to have systematic access to organized knowledge in order to use it to boost their creativity while making decisions on the one hand, on the other hand it exists mental activities and skills such as recognizing dependencies and estimating importance that are essential for decision-making [Pahl et al., 2006]. The generation and usage of the wide amount of information as well as expertise in a cooperative engineering field. Moreover, the handling of DfX as a communication tool in the early phases of developing a product may provide integrating of functions and management of requirements. Knowledge management and DfX can support the manufacturing firms to keep their in-house knowledge and expertise and use them for development and innovation [Jari et al., 2011].

Different approaches and methods will be next presented that enable to use the DfX criteria to do project-oriented research for crucial data and documents. Moreover, these approaches may provide the integration of the DfX criteria into the information supply of engineers within a development process [Henrich, 2006]. In order to develop a new concept and implement this into an information system, it’s important to create a proper structuring of DfX guidelines that is the fundamental requirement for an information system in the early phases of developing a product. There are several structuring options that will be presented and discussed below.

Structuring by origin from the product life cycle presented in Figure 6 is based on the structuring of guidelines corresponding to their importance to the many phases of the product life cycle. This type of structuring may provide an orientation to practical ways of thinking and, moreover, application of available areas in many firms such as manufacturing, assembly and sales is very simple. However, there is a significant lack between discrete aspects according to mutual and hierarchical relationships.

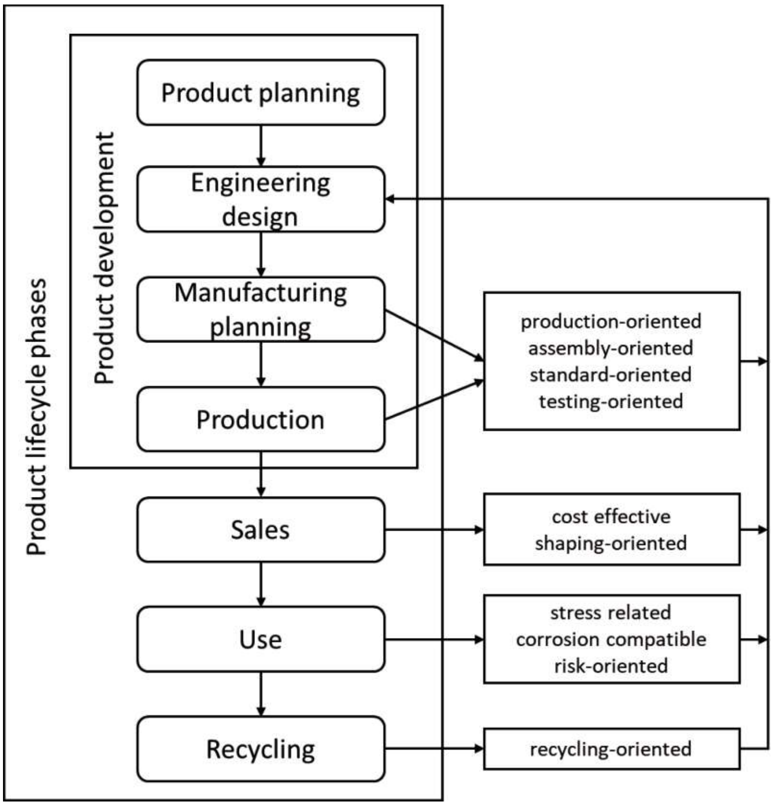

Figure 6, Structuring by origin from the product life cycle [Bauer, 2007]

Another type of structuring as shown in Figure 7 is hierarchical structuring. The big advantage of this DfX structuring approach is the identification of the hierarchical relationships between different DfX aspects, which may be also extended into different levels of detail. Furthermore, there is a structuring type according to characteristics, properties and objectives. In this approach hierarchical relationships are considered with respect to an aimed system [Bauer, 2007].

As mentioned above, a crucial success component in development processes is the information supply of the developers. Therefore, Design for X is very important for providing information to developers within the development process. In that connection, another approach is presented which provides inclusion of the DfX criteria and their weighting as further aspects for the definition of the context of development engineers. Moreover, this approach aims to capture explicitly the DfX criteria available in individual work steps and also tries to enable a corresponding context-based information retrieval system. In order to understand this approach in detail, a scenario [Henrich, 2006] presented in Figure 8. In this scenario, a developer starts working on an overall design within an ongoing development project. At the start of work, the corresponding preparatory documents (list of requirements, principal solution) are known. Moreover, the methods and tools used to prepare these pre-documents, and the relevant DfX criteria for the pre-documents and the overall design are also noted.

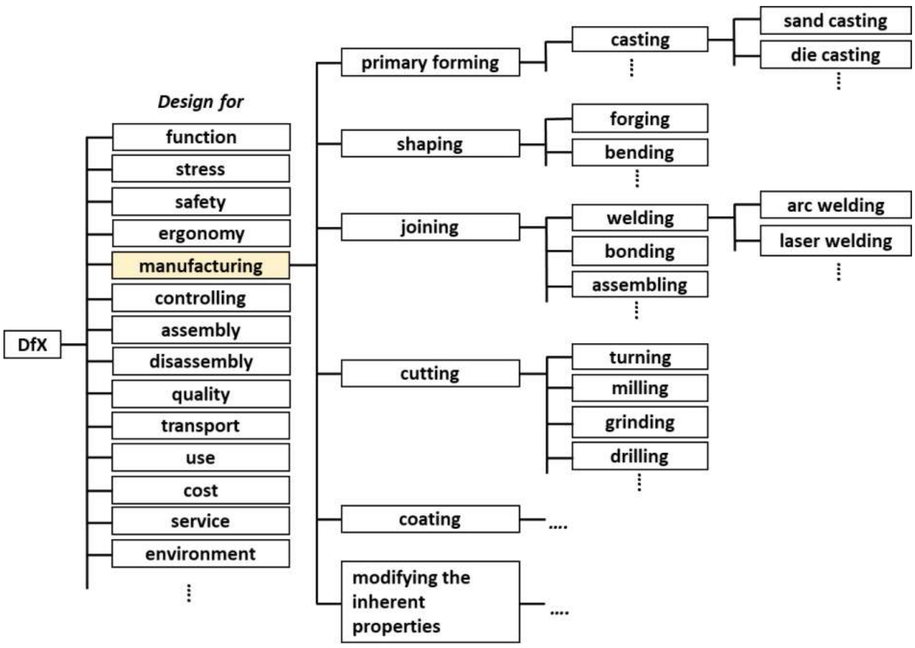

Figure 7, Hierarchical structuring [Bauer, 2007]

As shown in Figure 8 this scenario, the developer wants to start by looking for information during working on the overall design to secure his or her decisions. In addition to manually entered search terms, the above-listed information is also available to enrich the search. The application of this method is not limited to searching the enterprise resource, for example, in a search that the development engineer sends on the Internet, it may automatically add some key terms that match the relevant DfX criteria [Henrich, 2006].

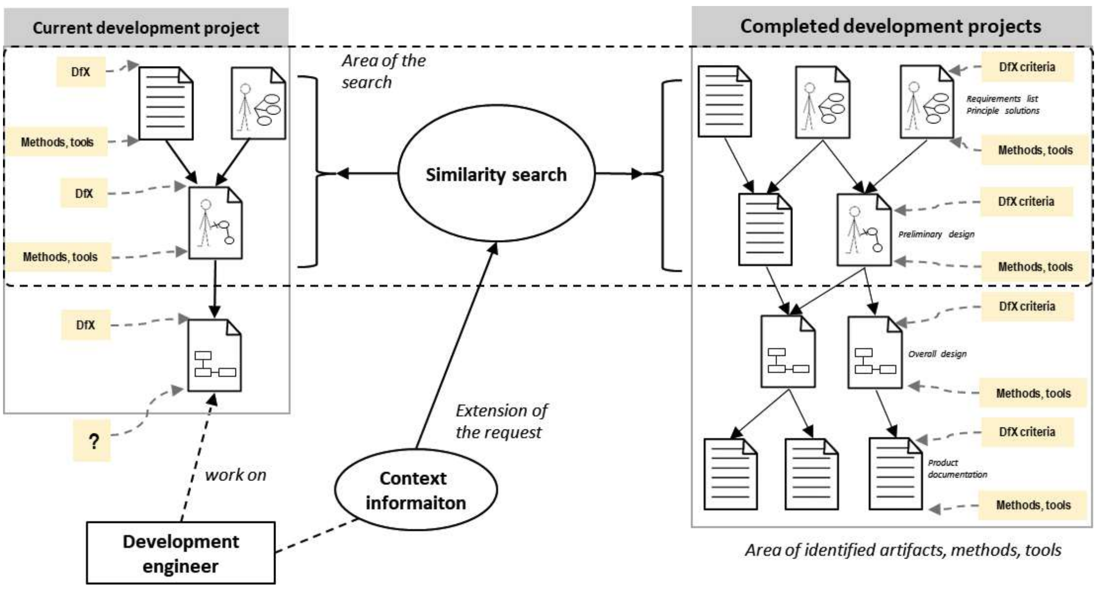

Figure 8, Scenario of a development engineer who starts with an overall design and decides on the use of suitable methods and tools [Henrich, 2006]

2.5 Product and Process Knowledge in PD

In general, company knowledge includes knowledge of employees that may be available individually and collectively in the cooperation of individual employees. In product development the knowledge of the developer consists of his knowledge, the experience with the given task as well as the available information and intelligence regarding the current situation. Moreover, knowledge in documents and systems as well as knowledge in products are other essential parts of corporate knowledge. Identification and develop of this knowledge are a sustainable competitive advantage for companies. [Petermann, 2011] [Schenkl, 2015] [Nonaka & Takeuchi, 1995] [Probst et al., 2006]

Product development takes place in a knowledge environment that is intrinsically complex and involves a wide range of factors, including organizational capabilities, market conditions and the development processes themselves [Sima et al., 2020]. It is commonly acknowledged that managing this complex, dynamic information base is essential to achieving effective and efficient development outcomes. However, knowledge is frequently dispersed among teams and functions, making cross-border exchange difficult. Concept generation, feasibility analysis, prototyping, testing, manufacturing planning and commercialization can all be considerably improved by capturing, representing and integrating product and process information across projects and over time [Sima et al., 2020].

The necessary knowledge is not always explicit but is also implicitly hidden in the minds of employees or developers and this knowledge content of developers has been allocated from diverse perspectives [Ponn, 2011]. Ahmed [2005] divided in four groups, which are product knowledge, process knowledge, knowledge about problems and knowledge about functions. This is refined by Vianello [2011] in the context of using knowledge from service delivery for the development phase as follows: Products, processes and procedures, changes, problems and revisions, projects, individuals and organizations, operating and life cycle capabilities, expertise and other knowledge content. According to Petermann [2011] the knowledge is divided into five classes based on content of knowledge, which are expert knowledge, product knowledge, process knowledge, soft skills and networks. The knowledge that the personnel possess includes specialist, product and process knowledge as well as soft skills. However, network is internal and external supplier and customers. [Schenkl, 2015] [Lindemann, 2009]

A process includes a sequence of activities with the use of information and knowledge as well as material resources. In product development, many different processes may be observed, for example, existing products are changed, new products are developed, products on the market are monitored for quality and safety, etc. Knowledge of processes have to be mastered by the employees in order to act in the company. Examples for process knowledge are knowledge about the development process, change management process, acquisition process or the certification process which are often company or industry specific. Product knowledge includes any knowledge of the company-specific portfolio of goods and services. Product knowledge can be, for example, knowledge of product design and characteristics, knowledge of the reasons for design decisions, and product and service functions. [Lindemann, 2009]

It is quite possible and effective to stabilize the PD process and improve it through waste reduction [Morgan & Liker, 2020]. In the product development, based on information regarding tasks, planning and objectives, further information is generated that describes the product. This created information is presented, for example, in the form of drawings, CAD models, calculations, test reports, parts lists or technical descriptions [Lindemann, 2009].

2.6 Knowledge-Based Engineering from the Perspective of KM

Being able to develop and complete a complex, high-quality product quickly and affordably, engineering design automation appears as a very important opportunity that can be realized by using knowledge-based engineering systems [Brown et al., 1995] [Verhagen et al., 2012]. For the achievement of design automation mainly capturing and storage of product knowledge, which consists of engineering rules such as standard engineering rules, or experiential rules, have to be provided. In general, traditional CAD systems involve geometric information for a single design, however knowledge-based engineering incorporates product knowledge and makes them available within a computerized application in order to models whole process to create design. In summary, the operation of KBE depends on not only landing and storage of necessary product knowledge, but also identification, acquiring, standardizing, and processing of available incorporated engineering knowledge are unavoidable activities for the guarantee of a capable and beneficial design automation [Sainter et al., 2000] [Kulon et al., 2006] [Sandberg, 2003]. Moreover, manufacturing use knowledge-based engineering systems to digitalize process knowledge and reuse it during the design and manufacturing stages. Adopting them enables the development of advantageous connections between intelligent systems and human experts [Mele & Campana, 2021]. For example, optimization of estimated assembly process in a short time and minimizing of the cost of possible changes can be achieved effectively through implementation of existing planning data that can be generated using data mining strategy [Kretschmer et al., 2017].

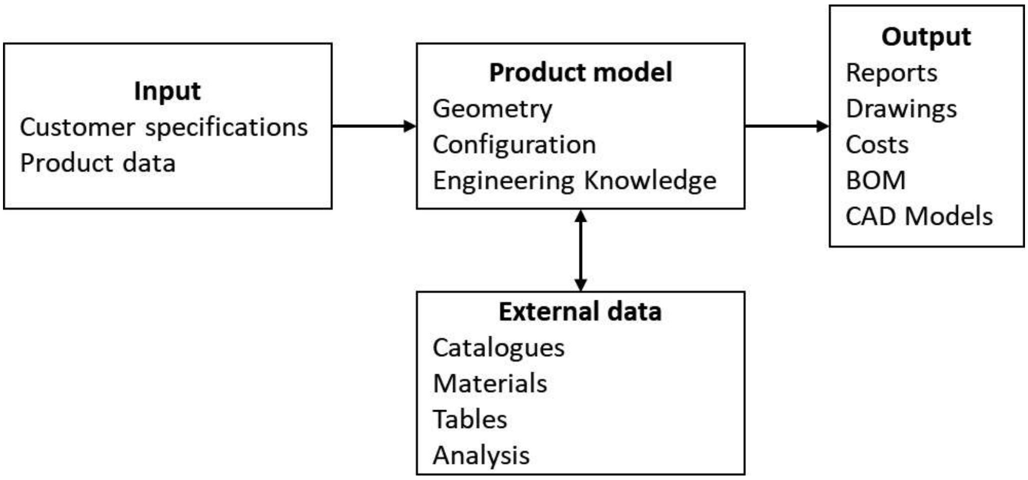

Figure 9, KBE Fundamentals [Sandberg, 2003]

Figure 9 presents the basic of KBE. According to KBE fundamentals, acquired and stored product knowledge is integrated in a product model by means of advanced software techniques. This integrated model is able to generate new designs that can be completed by modifying the product model's input requirements. This generation during a design task can be provided using less resources, cost and time in compared to a routine design. Therefore, increasing of freeing time of developers from repetitive design tasks can be used for improving the development methodologies to enable innovative and creative solutions [Verhagen et al., 2012] [Sandberg, 2003].

The product model includes the knowledge context with rules, which is usually categorized in following three groups: geometry such as parametric models, configuration, for example, a sport car and double exhaust pipes, and engineering knowledge e.g., manufacturing properties. Therefore, KBE aims not only generating a product model, but also integrating of manufacturing aspects or evaluation with respect to manufacturability is focused on, for example, evaluation of different rapid manufacturing alternatives. In a KBE-system external database provides storage of information such as standard parts and material properties. However, new product data or customer specifications as input have to be continuously delivered from product model. Outputs of a KBE-system are usually reporting, drawings, BOM and CAD models which are generated by the product model depends on input data [Sandberg, 2003].

For the creation of a KBE-system, various structured methodologies such as MOKA (Methodologies and tools Oriented to Knowledge-based engineering Applications) [Stokes, 2001], CommonKADS [Schreiber, 2000], and KNOMAD (Knowledge Nurture for Optimal Multidisciplinary Analysis and Design) [Curran et al., 2010] have been generated and applied. One of the MOKA's many advantages is the introduction of an iterative design process for KBE applications [Curran et al., 2010]. To understand these structured approaches, we can take the project MOKA as a reference method since MOKA is the most well-known and available as an international standard for KBE-system development. In Figure 10, six steps of MOKA are presented and summarize the primary goal of MOKA based on capture and formalize knowledge during the KBE development process. MOKA method begins with a conceptual specification of the KBE application and generation of a project plan which includes consideration of possible risks and technical matters. After specification and plan, the engineering raw knowledge has to be provided into a structured representation that is supported through ICARE forms (Illustration, Constraint, Activity, Rules and Entity forms). In the next step, MML (MOKA modelling language) which based on UML (Universal Modelling Language) used to formalize structured knowledge for the representation of knowledge in an acceptable and suitable form with respect to knowledge and software engineers. After formalizing developed model may be implemented to a KBE-system, and finally installation and distribution of model can be realized.

The creation of KBE applications is MOKA's fundamental objective, therefore, knowledge capture, structuring and re-use for newer products which has similarities to previous versions of same product can be continuously enhanced. However, MOKA and also other methods support knowledge and software engineers rather than the end user so that important aspects such as transparency, traceability, maintenance and better re-use of knowledge cannot be performed [Verhagen et al., 2012] [Sandberg, 2003].

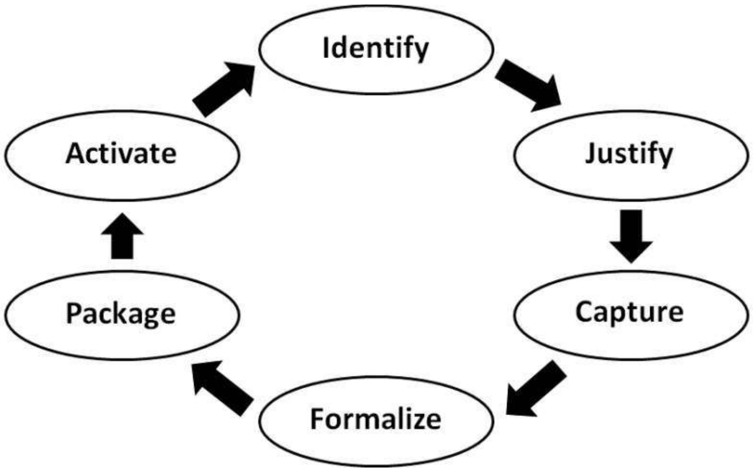

Figure 10, The KBE developing lifecycle according to MOKA [Stokes, 2001]

As a result, knowledge-based engineering (KBE)-Systems aim principally to apply explicit engineering knowledge for the automation of engineering tasks, which can be, for example, automation of design, configuration, analysis, and information processing tasks, etc. Therefore, implementation of knowledge into the product development is provided and the repetitive costly work between design and analysis can be carried out much faster [Catic, 2011]. However, an understanding and accessibility of knowledge in the developed KBE, in Figure 10, applications are very important since KBE-systems can become a black box that causes difficulties for transferring and understanding of the captured knowledge for especially new employees in a company. In comparison with KBE-Systems, this research focuses rather on perspective of knowledge management system, and the main idea is not to automate one single task using computer-executable knowledge about products and processes. Therefore, the procedures for knowledge management, DfX and communication in product development are investigated and studied. The new fact targeted in this research is to achieve dynamical identifying, capturing, storage and use of context specific or DfX-based knowledge in a knowledge management and communication platform.

2.7 Summary and Assessment

In this chapter, the state of research relevant to this work in the field of developing products, particularly in the early phases was highlighted. Tools and methods which are applied for the developing a product were also summarized regarding to knowledge management perspective. Accordingly, DfX emerged as an important method on the base of needs of categorizing knowledge and information. Moreover, an introduction to knowledge types and knowledge management, which will be covered thoroughly in section 3, was also made.

In the product development, generation of concepts and design solutions for innovative products needs both an organizational unit and a process. In this unit developers, especially in early stages of design, work as individuals or in teams for defining functions, searching suitable working principles and determination principal solutions. However, there is a large number of influencing factors from different areas such as usability, quality, manufacturing, assembly, ergonomics, environments and cost, which make development and design of concepts for technical products a knowledge intensive process. Applying and providing of knowledge, therefore, is a crucial factor, but the needed knowledge is not always explicit available. A non-negligible amount of knowledge is also implicitly hidden in the minds of the developers so that integration of experts' knowledge and experiences are necessary. Gain of implicit knowledge from different context during the application of past projects and make this acquired knowledge available in a structured way can support development engineers while making decisions for the creation of new products. Therefore, for the avoidance of many expensive and time-consuming changes in late phases of product development providing a fast information retrieval by using suitable methods and tools is needed. To achieve an effective information retrieval, an aimed acquiring and connection of knowledge from different areas is necessary. In this sense, use of DfX methods and approaches as a knowledge system and a codification strategy represents an important benefit since DfX related knowledge from specific areas of product life cycle can be reached to developers. There are different types of tools such as design guidelines, checklists and software tools, which support designers with a knowledge management perspective to identify a process or a product solution in concurrent engineering. However, well-structured knowledge in a systematic approach has to be available for designers to advance creativity, mental activities and skills during decision making processes. Different structuring approaches were presented in this section to determine an enhancement for the purposeful searching for vital information and documents in a new product development. Hierarchical DfX structuring is the most advantageous for this concept since the hierarchical relationships between different DfX aspects and their extension into different levels of detail can enable a context-based information retrieval system. The integration of the hierarchical DfX structuring and the information supply of engineers within a development process [Henrich, 2006] will be brought together in this concept in order to establish a fundamental for an information system with the aim of achieving a communication and knowledge management system. This main goal can support designers to access right product and process knowledge at an appropriate time during problem solving and decision-making process in the initial phases of product development. Furthermore, the lack of documentation and management of knowledge and experiences in product development cannot be ignored. This section gives also a summary of methods and technologies which used in the stages of product development and in summary, the waste of knowledge regarding to product and process hasn't focused enough on current methods and tools.

3 Knowledge Management in the Product Development

Knowledge is an essential prerequisite for solving difficulties in development processes and affects innovation speed positively, especially for decision-making [Remus, 2002]. Both the lack of personal knowledge accessibility to the business and the underutilization of employee knowledge's potential lead to waste in product creation, such as duplicate innovations or inconsistent decisions [Kaiser et al., 2008]. Knowledge management is therefore the key to corporate success, and which can be only provided with a structured and methodical approach to managing corporate knowledge resources and the targeted knowledge use in the organization, therefore, targets cost, time and quality may be achieved during the product development [Bullinger et al., 1997] [Klabunde, 2013].

There are many descriptions and specification relating to knowledge management. Knowledge management has four dimensions according to Wildner [2011]: knowledge as an object of KM; KM operations that manipulate the object; tools as resources that influence knowledge or knowledge carriers; factors as individual, social, technical, organizational, etc. Knowledge management's fundamental principle is collecting right information and transferring information to demanders by using appropriate technologies. In a knowledge management system, activities such as obtaining relevant knowledge from internal and/or external sources, refining and storing generated knowledge, sharing obtained knowledge through an adequate way according to users' needs, and also eliminating outdated knowledge have to be provided [Meža, 2012] [Ferreira et al., 2007]. However, to use knowledge efficiently, integration of acquired knowledge in the product development has to be executed. Additionally, it is significant to develop a company's knowledge base, which includes a variety of knowledge stocks and expertise. As a result, techniques or tools for organizing and managing the knowledge base can be made available [Klabunde, 2013] [Kaiser et al., 2008].

Furthermore, in recent years, knowledge management practices in product development have continued to evolve as new technologies and methods emerge. The main trend is the increasing use of approaches for machine learning and artificial intelligence to capture, organize, share and reuse knowledge [Jarrahi et al., 2023]. Another trend is applying big data analytics to derive new product insights from an increasing volume of design, testing, customer usage and other data [Wang et al., 2018] [Bi & Cochran, 2014]. The principles of flexibility also affect knowledge sharing that is faster and more flexible than sequential development [Singh et al., 2023] [Chau & Maurer, 2004]. Additionally, tools like Jira and Trello help with flexible workflow management and knowledge hierarchy. In addition, techniques such as crowdsourcing and online communities integrate more actively than customer knowledge during development to capture changing needs [Tseng, 2016].

In accordance with all the information provided, this chapter gives an overview about knowledge management activities with respect to phases of engineering design. Moreover, data, information and knowledge are described in detail to understand how knowledge distinguishes from data and information. In addition, knowledge dimension and knowledge management approaches are analyzed to identify suitable methods. In conclusion, available knowledge management software tools and technologies such as collaborative tagging and keywords extraction will be summarized and discussed to develop a new knowledge management and communication platform in relation to engineering design process.

3.1 Knowledge Management in Engineering Design

Section 2.1 describes the product development process in accordance with VDI 2221 [1993], which divides the process into seven stages. In this section, seven steps are categorized into four parts, and these are task clarification, conceptual planning, preliminary and definitive layout [Kaiser et al., 2008]. Knowledge management activities in those four phases of engineering design are defined in the following part.

As mentioned before the task clarification phase is for formulation and specification of the requirements, which have to be defined, assessed and documented systematically by means of consideration of all the stakeholders, for example, customers themselves, and production departments in the product life cycle [Klabunde, 2013]. In this stage knowledge management activities are definition of knowledge targets for organization of project teams by reason of optimal completion of goals. Moreover, suitable knowledge carriers, data bases and documents have to be identified and knowledge process is started [Probst et al., 2006].

In the phase conceptual planning, which includes determining functions, searching solution principles, conceptual selection and conceptual realization, knowledge management includes creativity techniques and knowledge acquisition in order to develop knowledge therefore use of existing knowledge is necessary [Klabunde, 2003]. Moreover, experiences and existing knowledge about tools and methods have to be transferred between project members in order to give the same degree of understanding of tools and approaches [Kaiser et al., 2008].

During embodiment design, defined technical and economical requirements in conceptual solution are fulfilled in a concrete and detailed technical shape. Additionally, dimensions, surface characteristics, and the defining of materials are finished in the subsequent detailed design [Klabunde, 2003] [Kaiser et al., 2008]. In this phase main knowledge management activities are knowledge use, transfer and evaluation. Reuse of documented knowledge in databases and providing of necessary knowledge for the embodiment design are main purposes [Klabunde, 2003]. Furthermore, acquiring and storage of new created knowledge is also very important for future projects.

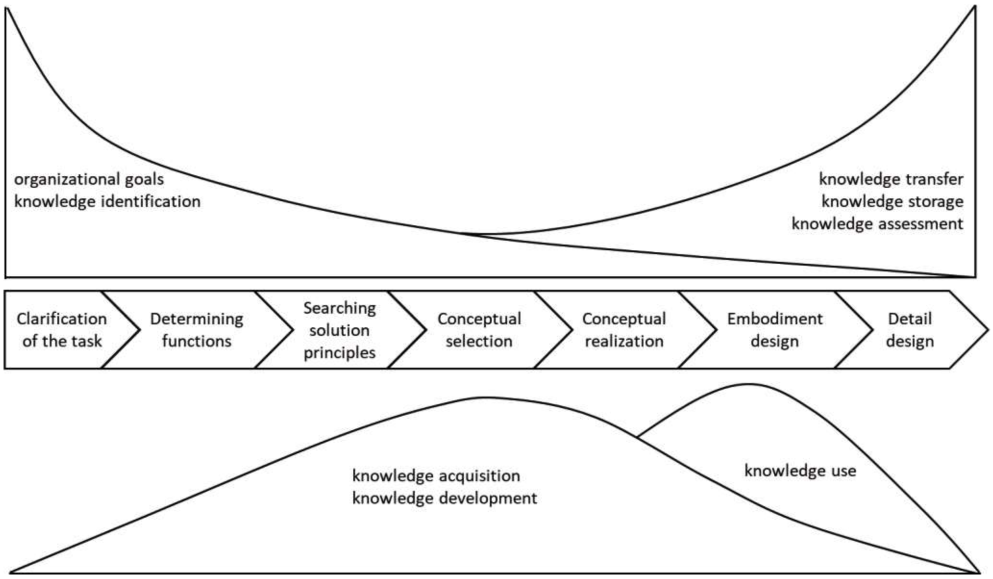

Figure 11, Relative characteristics of knowledge modules related to VDI 2221 [Kaiser et al., 2008]

In Figure 11, the relative characteristics of the knowledge processes on basis of the product development is presented. The early stages of product development indicate the need for modules on knowledge objectives and knowledge identification. However, knowledge allocation, storage and assessment as necessary modules appear in the late stages of product development. In addition, knowledge use has become very essential in concept realization, however, during synthesizing solutions the primary goal is on knowledge acquisition and improvement [Kaiser et al., 2008].

There are five value dimensions for mixed reality to enable prototyping, as indicated in Table 1. Through Creation and Configuration, Visualization, Knowledge Management, Integrated Analysis and Collaboration, these factors enhance design work. The inherent benefits of each were investigated with the aim of establishing verifiable value in which virtual prototypes in the virtual world may be used to supplement physical prototypes [Kent et al., 2021].

Table 1, Summary of dimensions of value [Kent et al, 2021]

Creation & Configuration	Create or set up a virtual or physical prototype with near-synchronous reflection in the conflict domain. Use shorter cycles and iterations to study form and function while interacting from the most efficient domain for the task.
Visualization	That provides better fidelity prototypes, often imperceptible internal geometry or circuitry, different loads for user testing, metadata, selection measures or previous iterations, you can learn more about and around real or virtual prototypes.
Knowledge Management	Information about prototypes can be created, saved and viewed. Note how it is used, who uses it, when it is used, and why. Instead of existing as a database or note, the data in this case is directly linked to a prototype and easily retrieved.

Integrated Analysis	Add direct interoperability with expert systems to the prototype so it can be explored, improved, and iterated. Ensuring capacity and compliance is simultaneously viewable in real time.
Collaboration	Enables building, viewing, interacting, collecting, and communicating prototypes remotely to foster collaborative work. By improving targeted prototypes, you can take the guesswork out of team development.

3.2 Data, Information and Knowledge in Product Design

Many theories relating to knowledge distinguishes between data, information, and knowledge. A collection of distinct, objective facts regarding a certain occurrence is referred to as data. Information is a message that has a sender and a receiver, and the meaning includes a new impression due to a group of data either as a written text or an audio transmission. Knowledge may be created from use and analysis of data and information, moreover, knowledge consists of experiences, values, contextual information and intuition. Therefore, knowledge is more comprehensively and deeply compared to data or information [Ferreira et al., 2007] [Hislop, 2005] [Meža, 2012].

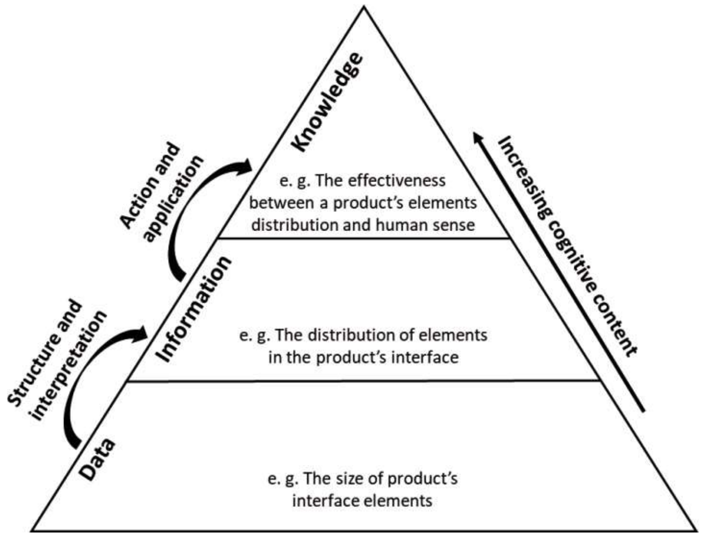

Figure 12, The relationships of data, information and knowledge [Yuan et al., 2006]

The link between data, information and knowledge is illustrated in Figure 12. The transition between different levels can be defined as an enrichment process. The goal-oriented connection of information enables their application in a specific area of work, that may be defined as knowledge which is always connected to an individual unlike data and information [Probst et al., 2006] [Gronau, 2001] [Kaiser et al., 2008]. In a product design knowledge is determined through the evaluated and organized information which is inserted into a context to manage decisions [Meža, 2012].

The idea of knowledge is defined and separated from other terms like data and information in the following section. As mentioned, the literature provides several definitions and viewpoints of knowledge. To build a meaningful concept, an appropriate definition of knowledge must be given in order to highlight significant issues that must be resolved. This investigation focuses on the knowledge description proposed by Probst, Raub and Romhart [Turki, 2014]:

“*Knowledge refers to the whole of proficiencies and skills, which persons apply to solve problems. This includes both theoretical findings as well as the practical rules of daily life and handling instructions. Knowledge is based upon data and information, but in contrast to these, it is linked always to persons. Knowledge occurs as an individual process in a specific context and manifests itself in activities.* “

Grounded on this description, since knowledge is predicated on data and information and is associated with an individual, therefore, it is necessary to identify the questions related to the development and application of knowledge. Although knowledge is created in a particular setting, this work also has to address and take into account how and where that knowledge is created, such as in what stage of the organization.

Furthermore, a number of crucial issues in proper knowledge management in product design emerge from an overview of data, information and knowledge [Cross, 2021]. For new hires, design knowledge covers many areas, from engineering to marketing, requiring the integration of many different technical and business ideas. It is difficult to manage this multidimensional knowledge across functions and projects. Second, design reveals important tacit knowledge, embodied in each individual's expertise and creativity. Capturing intangible knowledge through socialization and documentation remains a challenge [Parente et al., 2022]. Third, the iterative nature of the development process leads to ever-evolving and context-specific knowledge requirements. At each stage, an adaptive knowledge system is needed to connect different experts and information [Colli et al., 2019].

In this work main focus is the knowledge in product design, however there is not much research that has been done about the knowledge used in the product design process. Market knowledge, human knowledge, technological knowledge and procedural knowledge, which seen in Figure 13, are the four categories into which knowledge in product design is divided [Yuan et al., 2006] [Meža, 2012].

On one hand, human knowledge, which is internalized in a person, such as skills or creativity, is very important for the innovation and knowledge generation for designing products. On the other hand, market knowledge, which is interacted with the external interface such as customers, partners and suppliers, may be used to define objectives in product design. Additionally, innovations, publications, patents, know-how recipes, etc. are included in technical knowledge, which is a vital competency of design teams. A good design is enabled by procedural knowledge, which provides a framework for the efficient use of technological knowledge, market knowledge and human knowledge [Meža, 2012].

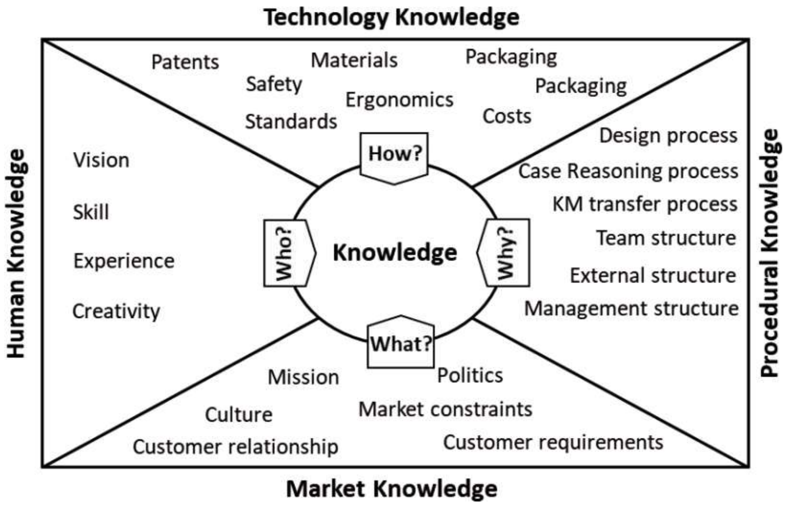

Figure 13, Knowledge in product management [Yuan et al., 2006]

3.3 Knowledge Dimensions

A generally valid definition of knowledge is difficult, because the term describes an elusive and abstract state of facts. Therefore, there were many scientific works that focused on the classification into different types of knowledge to characterize the concept of knowledge. An approach provided by Amelingmeyer [2013] is structuring of knowledge according to the level of explicitness and reference level. Concerning explicitness, knowledge can be differentiated in explicit and tacit knowledge. Experts possess implicit knowledge, which is highly specific, hard to define and challenging to share. Implicit knowledge is context specific and includes, for example, the knowledge that a craftsman has acquired in many years of professional experience [Schenkl, 2015] [Kaiser et al., 2008]. Moreover, according to Nonaka & Takeuchi [1995] there are two elements of implicit knowledge which are cognitive and technical. Technical aspects comprise knowledge, skills and talents whereas cognitive ones concentrate on mental models. In contrast to implicit knowledge, explicit knowledge is stable over the time and can be easily implied, formalized and communicated. Therefore, explicit knowledge can be standardized, structured and methodically stored by a systematic language form in documentation, databases, systems, technologies [Schenkl, 2015] [Bügel, 2004]. Explicit knowledge has to be inscribed and accessible for different people, which is the prerequisite to enable knowledge management systems [Ferreira et al., 2007] [Guerder & Yilmaz, 2013].

In the context of development processes another structuring of the knowledge regarding explicitness is also handed by [Wallace et al., 2005]. This approach defines three classes of knowledge which are explicit, implicit and tacit which are presented for product and process knowledge in Table 2. In this approach tacit knowledge is distinguished from implicit knowledge. Methods of knowledge gathering can be used to gain implicit knowledge. In contrast, tacit knowledge can neither be expressed nor acquired [Schenkl, 2015].

Table 2, Classification of knowledge according to [Wallace et al., 2005]

	Explicit knowledge	Implicit knowledge	Tacit knowledge
Process	Explanations about the process (rationale)	Understanding about the process (strategies)	Intuition about the process (insights)
Product	Explanations about the product (rationale)	Understanding about the product (relationships)	Intuition about the product (insights)

Besides structuring of knowledge, knowledge generation and knowledge transfer between different classes have to be summarized and discussed since gathering the tacit knowledge of professionals is one of the key objectives in this work. Figure 14 depicts Nonaka's knowledge spiral, which is a method for acquisition and conversion of tacit and explicit knowledge and serves as an approach for knowledge generation in product development projects. This dynamic spiral model proposes that tacit and explicit knowledge in organizations interact in four diverse ways to generate knowledge: socialization, externalization, combination and internalization. [Rosu et al., 2009] [Nonaka & Takeuchi, 1995] [Schulze & Hoegl, 2006] [Schenkl, 2015]

Socialization is the process through which people connect with one another and share tacit information through cooperative activities like talking, sharing experiences and working in a common space. Externalization transforms implicit information into explicit knowledge, and this change appears often through formal interactions, for example, expert interviews. [Schulze & Hoegl, 2006] [Schenkl, 2015]

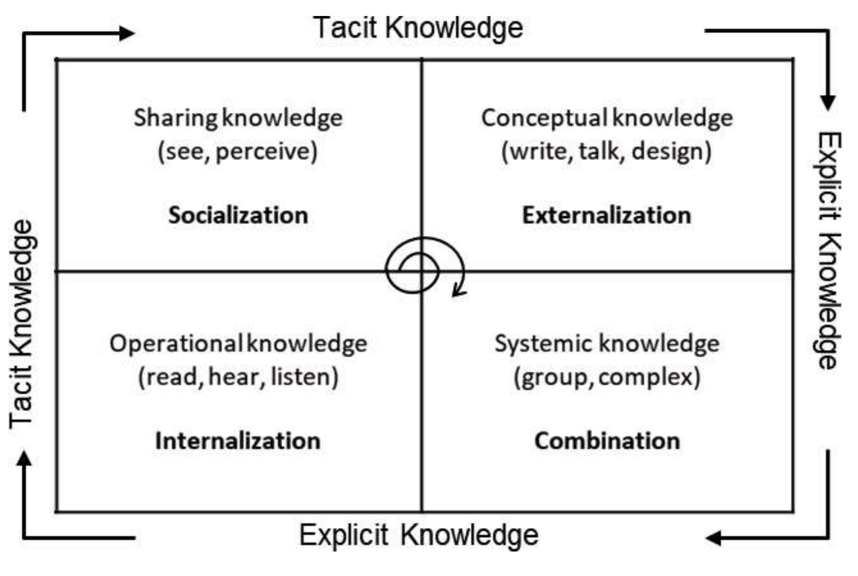

Figure 14, The four fundamental criteria for knowledge generation or methods of knowledge conversion [Nonaka and Takeuchi, 1995]

In the third interaction mode, combination process occurs through gathering, revising, organizing and synthesizing of available explicit knowledge for the generation new explicit knowledge. Finally, explicit knowledge is applied for example by learning in lessons from experience and experimentation so that explicit knowledge absorbed, embedded and converted into the minds of individuals as tacit knowledge [Guerder & Yilmaz, 2013] [Nonaka & Takeuchi, 1995] [Schulze & Hoegl, 2006] [Schenkl, 2015].

The contrast between implicit and explicit knowledge highlights major problems in the management and dissemination of design information. Unlike explicit knowledge, which can be recorded with artifacts such as documents and models, tacit knowledge is rooted in human experience and skill [Yang et al., 2019] [Sanford et al., 2020]. Capturing this tacit information requires socializing activities and contacting others to exchange ideas [Sanford et al., 2020].

On the other hand, exposing implicit information in explicit form has limitations. Acquiring knowledge through learning by doing and experimenting is also essential for clearly acquiring knowledge. The knowledge spiral model emphasizes reciprocal flows between explicit and implicit states, enabled through sharing, coupling, association and application [Chen et al., 2021]. However, it is difficult to maintain these flows of information between specialized professionals, industries and design projects. Therefore, to encourage information sharing, corporate culture and incentives are still very important. A combination of explicit and implicit knowledge types in design should be used in future studies to identify success factors in knowledge management [Zebal et al., 2019]. The full potential of design knowledge as a strategic asset can be unleashed through integrated frameworks that coordinate information flows, utilize digital capabilities, and encourage sharing.

3.4 Knowledge Management Approaches in Product Development

During the development of knowledge management, many concepts and models in theory and practice have been considered to manage the resource knowledge. In the following, various approaches are presented that provide understanding of knowledge building and guidance for enterprise knowledge management. First of all, three key knowledge management approaches are introduced, which are process-oriented approach [Heisig & Vorbeck, 2001], TOM model [Bullinger et al., 1998] and codification / personalization approach [Wesoly & Stolk, 2003]. After that, the building blocks of knowledge management [Probst et al., 2006] is described in thoroughly. Finally, the product knowledge management approach [Sainter et al., 2000] is highlighted since this method will be the primary area of attention for this effort.

- *Process-oriented approach*

Integration of knowledge management with corporate activities on a systematic basis is the core objective of process-oriented knowledge management, which enables knowledge work to be integrated into added value. Analysis of knowledge-intensive processes and the acquisition of information needed for process implementation are the key areas of attention.

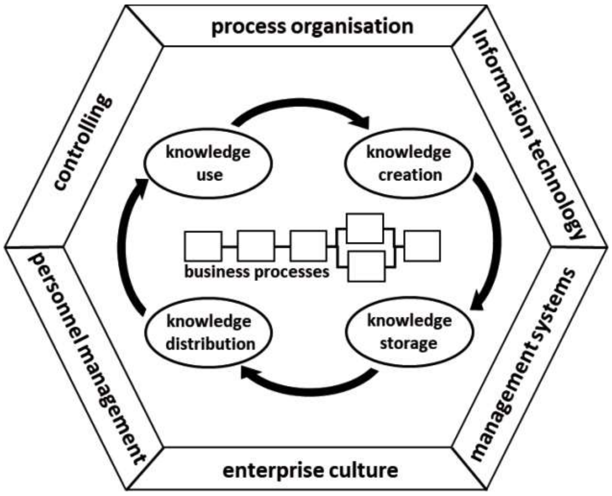

Figure 15, Structural framework for process-oriented knowledge management [Heisig & Vorbeck, 2001].

The development, storage, sharing and application of information are crucial activities that build up the closed process flow of knowledge management and enable its systematic use as shown in Figure 15 [Heisig & Vorbeck 2001].

- *TOM-Model*

The key objective of this knowledge management method is the holistic consideration of the design dimensions of technology, organization and human (TOM: Technik, Organisation und Mensch in German). A technological solution must take into account a variety of factors, these are, for example, the organization's ability to adapt and the employees' readiness to change [Cher et al., 2003]. Figure 16 shows a description of the dimensions and possible barriers to knowledge management implementation.

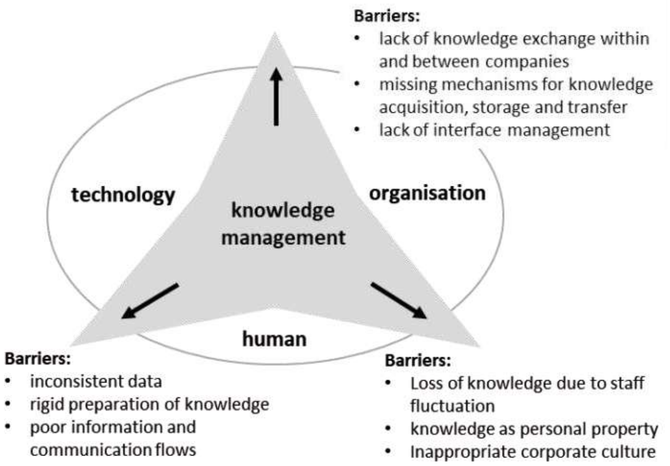

Figure 16, TOM-Model [based on Bullinger et al., 1998]

With this approach, information and communication technologies, for example, platforms, software and hardware, are intended as components of flexible knowledge management. In organization, development of methods for knowledge acquisition, storage and transfer are main purpose, therefore defining roles, hierarchies and expert networks are core tasks to provide a successful organization in knowledge management. For the last dimension human designing a corporate culture which can improve, for example, understanding, goal and responsibility so that a continuous flow of knowledge can be supported [Cher et al., 2003].

- *Codification and Personalization approach*

The codification aims to gather the employees' implicit knowledge and make it accessible in databases, therefore, existing knowledge can be multiplied and used effectively. Contrarily, the personalization strategy intends to simplify the sharing knowledge between groups and access to this knowledge by using technical systems, however, storing knowledge itself is not aimed, but enabling the transfer of knowledge [Wesoly & Stolk, 2003].

- *Building blocks of knowledge management*

In Figure 17, the blocks of knowledge management, which establish an oriented and coordinated framework, describe the task field of knowledge management. This approach consists of an inner and an outer cycle. The outer circle has determination of knowledge targets and their evaluation within the company. It is necessary to have six important factors in position to effectively implement knowledge management in a company. Identification, acquisition, development, distribution, preservation and use of knowledge are defined as principal processes of KM [Probst et al., 2006] [Guerder & Yilmaz, 2013].

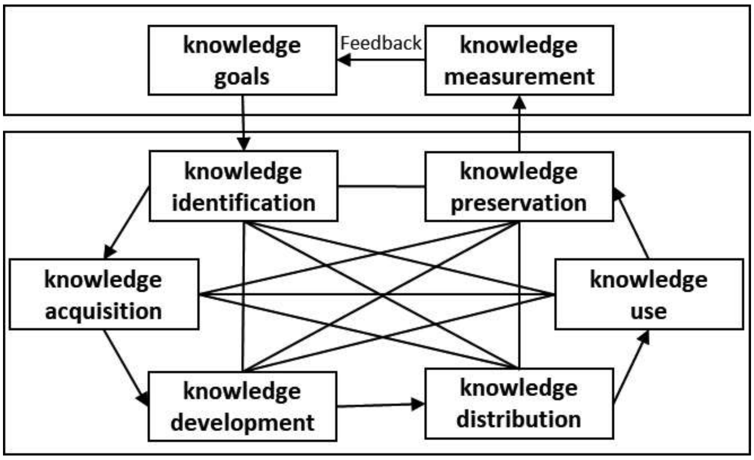

Figure 17, Building blocks of knowledge management [Probst et al., 2006]

Within the aims of knowledge essential objectives are specified. In the building block knowledge identification, available internal and external knowledge assets are analyzed and defined in order to provide transparency about existing knowledge resources. There are different tools, for example, knowledge maps, yellow pages, which execute transparency in knowledge searching activities for employees [Romhardt, 1998] [Probst et al., 2006] [Guerder & Yilmaz, 2013]. In this approach, knowledge acquisition aims to gain the necessary knowledge from external sources, on the contrary, knowledge development is for internal development so that new abilities, new products and better ideas can be generated [Probst et al., 2006]. Within the knowledge distribution availability of acquired and developed knowledge assets is provided. Moreover, sharing of experiences and simultaneous knowledge exchange are executed. Knowledge use is the last aim of knowledge management. Therefore, acquired and distributed knowledge has to be used effectively, otherwise the knowledge goals cannot be attained [Probst et al., 2006]. In the knowledge preservation, selection, saving and updating of essential knowledge assets must be provided in order to avoid losing of corporate memory. Finally, performance of knowledge management must be measured [Guerder & Yilmaz, 2013].

In a following work of Probst et al. [2012], in simpler terms, knowledge management has six main steps: finding, saving, using and sharing existing knowledge, as well as learning and creating new knowledge [Schenkl, 2015]. In this approach, in order to provide solutions for the tasks in knowledge management processes, different questions have to be realized and appreciate answers have to be provided, for example, how do I create transparency about existing knowledge? How do I get the knowledge to the right place? How do I protect against loss of knowledge?

- *Product Knowledge life cycle*

Another perspective is generated as an application development for the initial step within the advancement of a KBE system. Evaluation and identification of processes that is applied in an organization is the key for supporting tasks of knowledge management activities. For a successful application of knowledge domain experts have to get involved in the development processes to provide a clear impression of the product which is going to be modelled within the system. Therefore, realization of development process can be time-consuming and costly procedure. Moreover, poor knowledge engineering or poor knowledge quality can cause an inaccurate application, as in Figure 18 [Sainter et al., 2000].

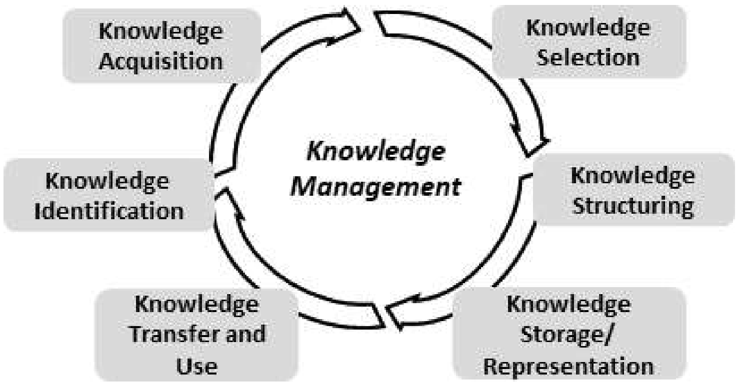

Figure 18, Product knowledge lifecycle [Sainter et al., 2000]

To make progress in acquiring knowledge in a company, it is important to have clear goals and a focused approach. The product knowledge lifecycle, shown in Figure 18, has four main parts. These include identifying and acquiring knowledge, preserving it through selection, structuring and storage, sharing and using the knowledge [Kaiser et al., 2008]. A well-functioning knowledge management system facilitates effective communication and the exchange of experiences, values, beliefs and work methodologies among individuals. Additionally, it aids in our comprehension and utilization of the available information.

Besides above-described processes there are three basic strategies of knowledge development based on [Gretsch et al., 2012] which are representation, communication and generation of knowledge. When it comes to representation, keeping the current knowledge of the organization for later use, making explicit the implicit knowledge and documentation of available knowledge, for example through knowledge maps. The representation of knowledge promotes the communication of knowledge. Communication aims to distribute knowledge within a company. Therefore, a certain employee receives in a particular situation access to just needed knowledge. Required knowledge that is not available in the company must be generated that occurs, for example, through the application of creativity techniques or acquisition of new employees [Schenkl, 2015].

There are some other important alternative classification models. The Munich model, which is based on Reinmann-Rothmeier's work in 2001, breaks down knowledge management into four main parts: representing, using, communicating and generating of knowledge. Wildner [2011] defines the concept of problem-oriented knowledge management which concentrates on concrete knowledge-related problems instead of a holistic knowledge management process. According to model by Turner and Makhija [2006], knowledge management includes four processes. Knowledge acquisition and its transfer to other employees, furthermore, the understanding of the gained information is influenced by the goals of the company and how the knowledge is utilized.

Besides the basic knowledge frameworks which are given above, other knowledge management methodologies offer alternate views for managing product knowledge.

- *Knowledge Ecosystems*

Efficient knowledge flow can be ensured through the way people, processes, and technology work together in the knowledge ecosystem. This approach focuses on networks, collaborative processes and platforms that support explicit and implicit knowledge exchange [Van der Borgh et al., 2012] [Clarysse et al., 2014]. The need to establish an environment that fosters a smooth flow of knowledge between people, processes and technology is emphasized by the concept of a knowledge ecosystem. First and foremost, it is necessary to consider both external and personal reasons for engaging in knowledge activities that need a psychologically safe and trusting environment where people feel comfortable discussing their thoughts. Finally, the system and the mode of interaction must be compatible with the types of knowledge being communicated, whether explicit or implicit [Clarysse et al., 2014].

- *Knowledge Maturity Models*

The frameworks provided by these models allow to assess an organization's current knowledge management capabilities against many different things, including people, how things are done, technology and the way people think and act [Crawford, 2006]. They depict increasing levels of maturity, allowing companies to spot gaps and decrease the complexity of their knowledge-based operations [Santos & Martinho, 2020]. Assessments can identify opportunities to systematically improve knowledge management maturity as well as strengths, limitations, and opportunities [Crawford, 2006] [Santos & Martinho, 2020].

- *Knowledge Metrics*

Knowledge measures create standards by which to measure and monitor the success of knowledge management programs. These may include assessments of knowledge generation, information sharing habits, user engagement, and knowledge base acceptance. Organizations can measure the knowledge management's effects on factors like productivity, being competitive as well as innovation using metrics [Bolisani et al., 2018].

Due to the diversity and dynamics of information required in areas of expertise and product lifecycles, adopting good knowledge management poses significant challenges in product development environments. To facilitate knowledge operations such as identification, capture, preservation, sharing and application, many frameworks have emerged. While early models focused mainly on systematization, recent perspectives emphasize the important role of socialization and human networks in knowledge transfer. However, making the most of product expertise remains challenging. Evaluation models are needed to measure talent and growth. The adoption of emerging digital platforms by organizations is slow, despite their promise Integrated knowledge management techniques that connect people, processes and technology need to be explored further. Individual findings or ideas can be turned into valuable knowledge for the organization by using solutions designed for the complex process of developing products, thereby driving creativity, productivity and innovation competitiveness.

3.5 Software Technologies for Knowledge Management

Technology dimension is a crucial precondition to provide an efficient knowledge management [Bügel, 2004]. This section discusses various software and technologies that can aid in the KM throughout the process of product development. In essence, various software tools exist to assist in knowledge management. Therefore, clarifying the possibilities of these tools according to the various knowledge processes is an important step.

To establish an efficient knowledge management system, both tacit and explicit knowledge should be focused. Moreover, available information and knowledge have to be acquired, stored and shared by various knowledge management activities. Table 3 gives an overview of the different types of software systems that are based on essential knowledge processes like generating, storing, transferring and using knowledge, as well as combining these processes together [Raimann & Back, 2000].

Another way of organizing software tools is shown in Figure 19, using the ideas from Lawton [2001]. These tools are grouped into different categories based on their functions and are presented in a model that helps with knowledge management. Different technologies such as indexing, classifying, storing, contextualizing, collaboration and application of knowledge have to be collected to support a knowledge management system.

Table 3, Core knowledge processes and software tools [Raimann & Back, 2000]

	Knowledge Generation	Knowledge Storage	Knowledge Transfer	Knowledge Use	Integration of Knowledge Processes
Intranet					■
Groupware	■		■		
Community Tools	■		■		
Search and Retrieval		■			
(Intelligent) Agents	■	■	■		
Knowledge Management Suites					■
Video/Audio Conferencing			■		
Data Conferencing			■		
Messaging/E-Mail			■		
Visualization Tools	■	■		■	
Personal Information Management					■
Data Warehousing	■	■	■		
Push Technologies			■		
Archiving/Document Management		■	■		
Learning Platforms				■	
Enterprise Portals					■
Workflow Management			■		
Summarization Tools		■		■	
Clustering	■				
Skill Mining		■			
Categorization		■			
Collaborative Filtering		■		■	
Expert Representation		■			
Problem Solving Tools	■			■	
Simulation and Modeling Tools	■			■	

The bottom layer of structure incorporates sources of explicit information that located in repositories as documents, E-mails or database records. Furthermore, technologies like word processors and database management systems are employed in this layer. The infrastructure layer is backed up by computers that store files, internet connections, and internal network services. Organizing and regulating the storage of information is the purpose of document and content management systems. Knowledge organization is supported with a corporate taxonomy to develop a knowledge map. Creating a knowledge map involves using tools to organize and categorize data and information. This can help with finding and sharing knowledge. To distribute knowledge for various applications, competence management, customer relationship management and knowledge portals are available at the next level [Sinha et al., 2004].

The subsequent section will focus on technologies that actively support knowledge management. Utilizing these technologies enables the creation of a knowledge management system, ultimately simplifying the process of KM. The way technologies are grouped and described varies in different sources. So, the technologies that are available are classified and explained according to the main processes involved in managing knowledge. In easier terms, this is about how information is created, stored, organized and shared. It also includes how we use and find this information.

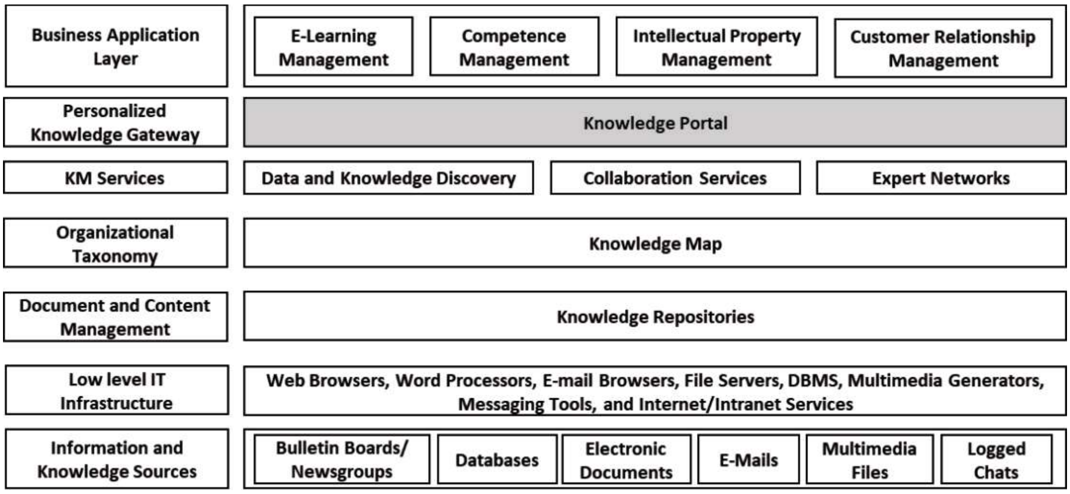

Figure 19, KM Architecture Model [Lawton, 2001]

Overall, generating knowledge involves doing activities to create, obtain and collect information. To make it easier to create important knowledge content, organizations use different tools like word processors, video editors and multimedia editors. These tools help them gather knowledge [Bergeron, 2003]. Moreover, document management systems (DMS) are used to enable explicit-to-explicit knowledge conversion since organizations produce documents that represent their explicit knowledge. Documents are all types of structured or unstructured information and important sources in the company [Lehner, 2000]. An efficient processing of these knowledge sources is made possible with a DMS. Identification of experts based on authorship of documents can also provide to create new knowledge that occurs tacit-to-explicit knowledge transfer. DMS provides functions to store, keep track of different versions, and manage the process of checking documents in and out [Bullinger et al., 2000] [Karagiannis, 2003], organization of documents, search and retrieval. In addition to document management, competence management is a key activity that focus on tacit knowledge. To identify knowledge gaps and core competencies, development of knowledge maps is necessary especially for distributed and decentralized organizations [Sinha et al., 2004]. New knowledge can be also generated from existing information and knowledge bases by using knowledge discovery method that contains various approaches for analysis text and numeric data. In that category, a tool for data extraction could be mentioned as an example where it shows the patterns and relationships among data in order to learn more about basic data [Sinha et al., 2004]. Furthermore, data capturing technologies [Bergeron, 2003] are applied in the knowledge generation to correctly convert the data into a machine-readable format e.g., web data capture and optical character recognition (OCR) [Antonova et al., 2006].

The way that knowledge is stored is another important factor. There are numerous technologies and techniques for storing of data, information and knowledge, e.g., data warehouses, knowledge bases and databases [Antonova et al., 2006]. This solution is the principal component of a knowledge management infrastructure. A data warehouse is intended to provide and process large amounts of data, especially quantitative data. The input for the data warehouses usually is provided by operational (from the individual departments) and external databases [Karagiannis, 2003]. Another type of warehouses is knowledge warehouse which focused more on qualitative data compared to data warehouses. This type of repository stores knowledge generated from a variety of sources, including work processes, news articles, external databases and Web pages [O'Leary, 1998] [Antonova et al., 2006].

Another crucial component in a KMS is knowledge codification and presentation. There are many different approaches and technologies available for the representation of the knowledge. In many cases, specific information has to be represented for the user to achieve efficient use of knowledge. In order to get information from previous problems or cases, case-based reasoning system is an advantageous solution for the companies [Tiwana, 2000] [Antonova et al., 2006]. Even though organization of information is provided in a structural form in a case-based reasoning system it may be problematic for accessibility of right information. Experience and knowledge of user about the scheme is very important to achieve an efficient search since organizational structure can have a large and deep hierarchical structure. Building domain knowledge into the delivery mechanism, therefore, is an approach to support knowledge access since search and browsing especially at design applications can be provided. Technologies for the knowledge organization are key opportunities for the development of useful classification schemes [Antonova et al., 2006] [McMahon et al., 2004]. Technologies in this category, such taxonomies and ontologies, make it possible to arrange disorganized content and knowledge elements in accordance with organizational goals. By using taxonomies, these tools transform the explicit understanding of the knowledge pieces into another explicit knowledge, therefore, well-organized documents enable users to identify and learn with visual presentation of the knowledge repository [Sinha et al., 2004]. Ontologies, in general, define concepts and the common vocabulary used in knowledge management systems to facilitate tasks like search, storage and representation [O'Leary, 1998]. In order to codify knowledge for a better knowledge presentation, many different models are generated in the artificial intelligence field based on rule-based approach. Some of these models are, for example, production models (rule-based models), procedural model, semantic nets [Antonova et al., 2006].

To provide an effective knowledge use and retrieval, different technologies and tools are available. The following presentation and discussion will focus on some of the most well-known tools and technologies. One technology is the expert systems which provide a forum by using knowledge bases and peer-to-peer support. The main focus is on supporting users to achieve recommended solutions. In general users are guided by expert systems to have recommendations for decision making that happens when solutions are saved for later use, from tacit to explicit. User can also communicate to expert, that occurs tacit-to-tacit, when the systems answer is not enough to learn the logic of decision. Common characteristics of these tools are expert identification, communication and collaboration [Sinha et al., 2004] [Antonova et al., 2006]. Other systems are decision support systems that enable knowledge use in organizations by means of reviewing and modifying the data that has been saved. In this concept many technologies, e.g., expert systems and simulations tools, can be used to spread decision support tools in practice to perceive and manage stored information in the data warehouse [Bergeron, 2003]. Moreover, Customer relationship management (CRM) and Enterprise resource planning (ERP) are popular applications that can be used in the area of knowledge management. Essential understanding of the business, clients and partners can be available and represented by means of these technologies [Housel & Bell, 2001]. ERP's primary goal is to integrate various forms of knowledge and show them to users [Antonova et al., 2006]. Main objective of CRM is to assist support personnel consistently to acquire appropriate knowledge about the products and services through experience of customers [Sinha et al., 2004]. To facilitate the knowledge use and processing, visualization tools are also another opportunity to minimize the time desired for professionals with knowledge to collect confusing processes especially when an adequate transfer of graphics and animations is provided. Compared to a text presentation on the same issue, slide presentation and different images are more accepted and effective [Bergeron, 2003] [Antonova et al., 2006].

The focus of this part will be on knowledge transfer, exchange, accessibility and search tools. Web technologies as the basic technology for knowledge management portals provide a variety of tools and services which enables platform-independent access to applications via an https connection. To achieve an effective timely access to and sharing of knowledge, this technology can be used very successfully for the creation of knowledge portals, since web services provide access to distributed knowledge management tools. In fact, Web technology provides not only the exchange of knowledge about distributed knowledge resources such as different representational and communicational media but also the exchange of functions of knowledge management tools. In conclusion, due to the rapid advancement of Internet technologies, interactions and dissemination services, web-based knowledge management tools and services provide a significant advantage in the idea of knowledge management [Antonova et al., 2006] [Karagiannis, 2003]. In order to collaborate and communicate employees, groupware is an often-used electronic technology that provides collaboration of the teams [Liebowitz, 1999]. When users cooperate and communicate using a messaging app or a real-time messenger, for instance, knowledge is converted mostly from tacit to tacit in this category [Sinha et al., 2004]. Some of groupware technologies are, for example, shared authoring tools, electronic whiteboards, multimodal conferencing, online screen sharing, e-mail as well as electronic meeting systems (EMS). The basic functionality of these technologies is to provide a computer-based communication channel so that employees can be directly involved and supported as a source of knowledge [Sinha et al., 2004] [Antonova et al., 2006] [Karagiannis, 2003]. Knowledge sharing is another relevant aspect that was also discussed in the literature since duplication of knowledge is not as simple as information. Knowledge is highly context based and can be shared synchronous or asynchronous [Tiwana, 2000] [Liebowitz, 1999]. Web-based information sharing is still in its development, for instance, technologies like the digital staff directory, network workspaces, yellow pages and mind-mapping can only make the process of sharing knowledge faster. It is crucial to develop business culture and expert motivation to properly exchange information [Antonova et al., 2006]. Searching and finding information on the Internet has been accomplished with a wide variety of Internet search engines that are mainly applied to guide users to search actively for knowledge. The most important part of the Internet is the World Wide Web (WWW), a collection of linked websites in HTML format. Internet programming languages and tools such as JavaScript, JAVA, PHP, become more relevant since the Internet is the backbone of the IT infrastructure. In this respect, search engines analyze documents on the Internet and enable the use of web pages by providing document catalogues, categories or short summaries of the HTML pages. This development is used as knowledge navigators to achieve more intricate and thorough searches in knowledge bases and warehouses [Housel & Bell, 2001] [Antonova et al., 2006] [Karagiannis, 2003].

The intelligent online agents, commonly referred to as software robots or bots, are another type of technology. These tools use the most recent advancements in artificial intelligence to gather data from intranets, commercial databases and the web [Karagiannis, 2003]. Software agents are encapsulated computer systems that autonomously accept user questions and transform them into the adequate language. In this context, acceptation of natural language input is a key factor which is possible by means of natural language processing (NLP). NLP is a computer-assisted method of text analysis with many practical goals including machine translation, summarizing texts, answering questions as well as finding information [Antonova et al., 2006] [Chowdhury, 2003] [Cambria & White, 2014]. For example, information retrieval systems, which are based on NLP, aim to achieve more precise, complete information through searching a collection of natural language documents with respect to user's real information need or rather user's query. Compared to database systems that needs structured data, information retrieval systems execute unstructured natural language text [Voorhees, 1999]. NLP is also utilized in Information Extraction. Main focusses in the application of Information Extraction are the recognition, tagging and extraction into a structured representation through a large amount of collected text to provide question-answering, visualization and data mining [Chowdhury, 2003] [Liddy, 2001].

The use of collaborative or unstructured tagging combined with NLP represents one of the primary components of this approach. Therefore, the next section presents an overview of collaborative tagging and covers some of the motivations for its growth. Moreover, some of the problems respect to collaborative tagging approaches for knowledge organization are reviewed and discussed.

Adopting these tools to support product development presents some significant potential and challenges, based on a deep understanding of knowledge management software technology.

Integrating increasingly diverse solutions across distributed teams, domains, and lifecycle stages is a big deal [Gogineni et al., 2019]. Instead of promoting smooth knowledge flows, there are too many discrete technologies that fragment knowledge [Abubakar et al., 2019]. Can enhance the adoption and effectiveness of a central team of collaboration platforms that are adaptable and aligned with mission-critical workflows [Abubakar et al., 2019] [Malik & Al-Toubi, 2018].

Compared with conventional interfaces, emerging technologies such as AI assistants and mixed reality can improve information access and contextual communication. However, participation and acceptance in the organization lags behind [Paschen et al., 2019]. Technology, culture, dynamics and change management all need to be integrated into comprehensive implementation plans.

Increased measurement capabilities and mature modelling help assess the complexity of knowledge management and focus on high-value changes. However, solutions must closely follow market developments and technological advancements. Personal knowledge can be transformed into organizational capital to enhance innovation and productivity through sustained engagement combined with flexible tools rooted in knowledge leadership [Hislop et al., 2018].

3.6 Collaborative Tagging

As already mentioned, an effective use of the available knowledge, knowledge sharing and improved accessibility to knowledge are important aspects for a knowledge management system. To realize these aspects information retrieval has an essential role. With an effective information retrieval method, the stored information can be processed and offered in such a way that, if there is a specific need for information, it can be searched precisely and used completely. Therefore, some new web-based information management tools have developed which improve individual knowledge work, group communication and collaboration. Web 2.0 is referred to in this sense as a collection of technologies powered by people that facilitate and make collaboration easier. The tagging system, also known as collaborative tagging, social tagging, folksonomy, etc., is one of the most widely used Web 2.0 tools [Huang et al., 2012]. Tagging is an approach which allows users to tag or categorize web pages and also use keywords to annotate online resources, then let individuals see them [Voss, 2007] [Macgregor & McCulloch, 2006]. Collaborative tagging process doesn't need any professional basis, therefore this process is easy to be applied by users who is able to contribute information in the way of keyword-based tags and link these tags to digital resources [Huang et al., 2012] [Ghani, 2009]. Collaborative tagging has two main goals: On the one hand, personal categorizations can be generated simply to retrieve information later; on the other hand, searching for related resources, which are assigned keywords by users, is possible through collaborative use of attached tags [Huang et al., 2012].

Users, resources and tags serve as the three core parts of collaborative tagging systems [Marchetti, 2007] [Huang et al., 2012]. Users, who is also called taggers, are connected in groups having a range of various interests, requirements and objectives. Users apply a tagging mechanism to generate tags for available resources and sharing content, therefore, they can browse or search for the data afterwards through tagging. Resources can be described as the items that users assign with keywords, and resources can be connected with the various links that establish the base of current Web. Tags, which are essentially metadata about the resource, serve as the link between a user and it, and the chosen tags are accessible on the Web [Marchetti, 2007] [Huang et al., 2012]. In this way users can be connected to each other by means of generated tags and also discover other users with similar purposes, therefore, users of an interactive tagging solution can collaborate socially in addition to obtaining information [Wu et al., 2006]. The number of websites that offer collaborative or unstructured tagging has grown throughout the past few years. Some of the popular collaborative tagging sites are, for example, del.icio.us (http://del.icio.us) an archive of URLs that enables user to assign tags to a Web resource by its URL this is also known as social bookmarking website. Furl (http://furl.net), Reddit (http://reddit.com), and Digg (http://digg.net) are also web services for bookmarks [Hammond et al., 2005] [Voss, 2007]. Moreover, Flickr (http://www.flickr.com) is an archive of photographs and a photo sharing website which allows user to share and tag his personal photos [Winget, 2006] [Voss, 2007] [Wu et al., 2006] [Grudin, 2006]. Technorati (http://www.technorati.com) offers collaborative tagging services that let writers or bloggers tag the entries on their blogs in order to collect data from weblogs [Marchetti, 2007].

Collaborative tagging systems is a significant opportunity to support KM activities in an organization, like information storage and retrieval. However, achievement of high consistency between different taggers is a problem when users retrieve or present resources with keywords. One important fact that still need to be improved is control of the vocabulary for tagging. According to analyzing of existing folksonomies or collaborative tagging systems by different literature the following weaknesses were pointed out and these problems cause inconsistencies and decrease the effectiveness of the tagging [Huang et al., 2012] [Wu et al., 2006] [Marchetti, 2007] [Golder & Huberman, 2005]. Therefore, an integrated tagging system for any knowledge management system has to be focused with respect to following problems, for example, synonymy, homonymy, polysemy, various lexical forms, misspellings or other spelling variations.

Synonyms: various words have the same meaning, for example, ‘car’, ‘auto’, ‘automobile’, ‘machine’, or ‘motor vehicle’ are different words for the same concept. Identification of synonyms are not supported for existing collaborative tagging systems, that causes a poor link of collection and ineffective search of important resources.

Polysemy: the similar word can have multiple related meanings in various concepts, for example, the word ‘field’ represent a piece of land or a branch of knowledge. If many terms have the same form but have different meaning that is defined as homonyms. Distinguishing between polysemy or homonyms is also another significant factor to achieve a collaborative tagging system.

Different lexical forms and lexical anomalies are also important factor in a tagging system. Superfluous vocabularies have to be reduced or removed, for example, leading articles, prepositions, conjunctions, etc. In this context, different term variations can be used for the same concept such as singular and plural forms (‘cat’/ ‘cats’), different verb conjugation (‘work’/ ‘working’), name-adjective couples (‘energy’/ ‘energetic’). Furthermore, different possible spelling (‘neighbor’/ ‘neighbour’) or misspelling errors (‘relgion’ instead of ‘religion’) of the same word can appear.

In view of this, according to an overview on cooperation tags, the use of these technologies for knowledge management provides both opportunities and challenges [Zhang & Cranshaw, 2018] [Emerson & Berge, 2018]. They provide an important opportunity to improve the reuse of knowledge, enabling developers to specify keywords for artifacts such as CAD models, simulations and project documents. It may also improve search and discovery at all stages of the project. However, it serves to remind us that the task of maintaining a linguistic consistency among users is still difficult, for example with synonyms and other forms of words [Orenga-Roglá & Chalmeta, 2019].

It is difficult to manage individual and shared knowledge since there can be a variety of meanings in terms of tags [Emerson & Berge, 2018]. Users are motivated by different incentives, which reinforce the need for societal features. To establish the best labelling strategy for design knowledge combining flexibility and structure, research should be conducted. To convert product knowledge into valuable intellectual property, appropriately marked repositories can significantly enhance access and reuse [Orenga-Roglá & Chalmeta, 2019].

3.7 Summary and Assessment

To manage a product and its development process, avoiding and handling critical situations is an essential task which can be supported through the deployment of a knowledge management methodology that is effectively integrated. Many organizations and businesses, however, have not yet realized the value of knowledge management and its key skills. Knowledge storage, creation, development, sharing, codification and use are success factors for an effective product management where teamwork and communication are main characteristics of a product development process. If human and company knowledge stay in the individual level reuse of the existing knowledge cannot be provided for the multidisciplinary development team, therefore, a sustainable generation and integration of knowledge have to be ensured before individuals leave, or development projects are completed. However, generation of knowledge in a teamwork is a difficult process since team members have to create, consider and improve ideas, moreover, it needs also an iteratively process to achieve a corporate success. To facilitate that, a structured and systematic handling of human and company knowledge have to be provided in the organization. In this respect, on the one hand, databases and systems for exchanging information must be prioritized; on the other, methods for simplifying collaborative processes must be provided. Implementation of these technologies into a KMS can bring advantages for gathering right information and its transfer to demander in the product development.

In this section different perspectives were presented for the planning, control and creation of a knowledge base in a company, and also for the characteristics of the knowledge processes to support activities initial stages in a product's development. The task clarification, conceptual planning, preliminary and definitive layout were reviewed to define principal knowledge management activities in the engineering design. Important facts may be the definition of knowledge targets and knowledge carriers in the task clarification phase. Moreover, knowledge acquisition through creativity techniques is an important requirement in the conceptual planning. In addition, knowledge use, transfer and evaluation appear as necessary modules during embodiment design.

To achieve the main goal of this concept and understand knowledge for this work an appropriate definition of knowledge was referenced and discussed. The fundamental unit of knowledge is made up of data and information, which is the most significant aspect of the knowledge concept. Additionally, knowledge is produced in a particular setting with a connection to an individual. Using and evaluating data and information play an important role for knowledge development since design knowledge that depends on a context, such as experiences, values and contextual information, is determined through the evaluated and organized information in a product design. In addition to knowledge definition, focusing on the classification into numerous forms of knowledge and structuring of knowledge according to the level of explicitness were also summarized and discussed. Two classes, explicit and implicit knowledge, are important for this concept. With the use of current databases, systems and technologies, explicit knowledge may be organized and methodically stored. However implicit knowledge which consists of cognitive and technical elements cannot be easily structured and stored. Before structuring of implicit knowledge, especially know-how, skills and abilities of experts have to be generated and transferred. In order to realize implicit and explicit knowledge creation and conversion in product development dynamic spiral model of Nonaka that has four interaction modes (socialization, combination, internalization and externalization) has to be considered in any knowledge management concept. In this regard, the adoption of a knowledge management strategy not only helps firms satisfy their requirement to manage technical knowledge, but also the above discussed approaches and techniques have to assist in knowledge management. This section presented many different KM models that have been developed for the managing the resource knowledge. These models base on different perspectives, for example, process-oriented approach, TOM model, codification strategy. Since a comprehensive knowledge management system is aimed, six building blocks by Probst et al. [2012] and product knowledge life cycle are going to be main focus to establish a goal-oriented development of knowledge within a company.

Another aspect for a knowledge management concept is the existing technologies. An overview of technologies and software tools based on the main knowledge management processes was also provided since technology dimension is a precondition to realize a product knowledge lifecycle. For a comprehensive concept, core KM processes like generation, storage, codification, transfer and use of knowledge must be supported by means of different technologies and software solutions. Therefore, the available technologies are classified and elucidated according to knowledge management processes. In summary, for the generation of knowledge different authoring systems are available to facilitate knowledge acquisition within organizations. Storage of the knowledge can be provided via databases, knowledge bases, data warehouses. To support the codification and representation of knowledge case-based reasoning system, various taxonomies and ontologies are important technologies for knowledge organization. Technologies like expert systems and decision support systems are often used applied technologies to facilitate knowledge usage and retrieval. Furthermore, Web technologies as the basic technology for transfer and searching of knowledge supply a variety of tools and services, for example, network workspace, yellow pages, mind-mapping. Technologies like collaborative tagging and natural language processing can provide an information retrieval solution. A tagging and scanning mechanism can be used for the collection and linking of acquired knowledge according to DfX principles.

4 Communication and Cooperation in the Product Development

In mechanical engineering, the proportion of mechatronic products has greatly increased in recent decades. Mechanical engineering, electronics and computer science components intelligently interact in the field of mechatronics [Lindemann, 2009]. The most promising product innovations arise from the interdisciplinary product development and the proportion of purely mechanical products is becoming increasingly smaller. For companies, this development means the opportunity for innovation and intelligent products, but it also poses new challenges. New methods and requirements have been developed and implemented to provide efficient possibilities for interdisciplinary product development, however, human factors are often neglected [Neubauer et al., 2012]. To achieve a creative environment, collaboration must be applied without restrictions, because the exchange of information enables creativity and innovation. According to Lu et al. [2007] collaboration requires a team that works on tasks, not only sharing resources and results, but also having the common goal. On the other hand, cooperation is defined as the mutual achievement of project goals according to Steinheider [2001] and consequently the interdisciplinary cooperation is defined through the dimensions of coordination, communication and knowledge integration. In this section, main focus is on human factor and especially his communication with each other in the development teams since communication provides an essential function for the exchange of information. The human dimension, communication, and the use of appropriate communication technologies in interdisciplinary teams of product designers are also briefly discussed.

Eigner et al. [2014] defined communication as the verbal and nonverbal exchange of information between a message's sender and recipient. He references basically to the sender-receiver communication model, which provides for the transmission of a message through a channel. However, he also emphasizes that there is a high risk of misunderstandings with this type of communication and that both sender and receiver of the message must be aware of this in order to avoid these misunderstandings. Feith [2013] describes communication with the constitution model. This model defines communication as the joint development of the communicative message by the participated interlocutors. The participants themselves create the meaning of the linguistic act interactively. Therefore, the receiver of the message does not behave passively during the conversation and tacitly receives information from the other participants, but actively shows that information has been transmitted and understood. This behavior reduces the chance of misunderstanding since the receiver makes it clear what and how he understood the message. The sender can therefore immediately clear up any misunderstandings.

One common model that explains the fundamentals of communication in Figure 20 has been defined by Shannon & Weaver [1976]. This communication model describes that a sending system transmits information generated by a source to a receiving system. The transmission to the recipient takes place via an information channel (medium), the information generated by the source being encoded before sending. The recipient decodes the message and makes it available to the destination. However, the coding should be identical for the sender and receiver to prevent misunderstandings since misunderstandings can occur from the fact that conversation partners form their own interpretations from the information given to them. A source of interference reduces the quality of the information [Grieb, 2007].

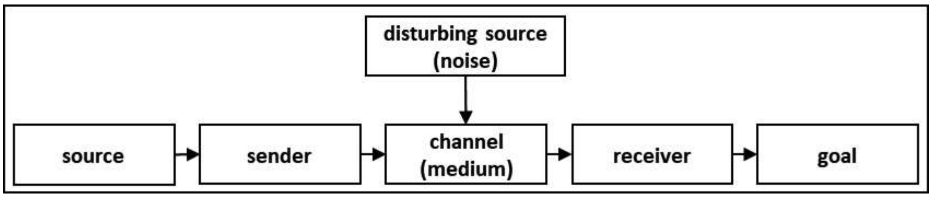

Figure 20, Communication model according to Shannon & Weaver [1976]

The communication square model by Schulz von Thun represented in Figure 21 addresses the difference between sent and received messages [Eigner et al., 2014]. The communication square states that communication occurs on four distinct stages:

- *The factual level*: The factual information is to be communicated in this level. The task of sender is giving data, facts and statements clearly and understandably.
- *The relationship*-layer: At this level it is decided how the information should be communicated depending on the relationship and opinion towards the interlocutor.
- The self-revealing: This level offers space for self-expression and thus the possibility to decide to reveal something. To put it more clearly, the sender tells, for example, his or her motives, values, emotions etc.
- The appeal: At this level it should be made clear to the other person what is required of him or her, based on the transported message. This level contains the advice, instruction and effects that the speaker needs.

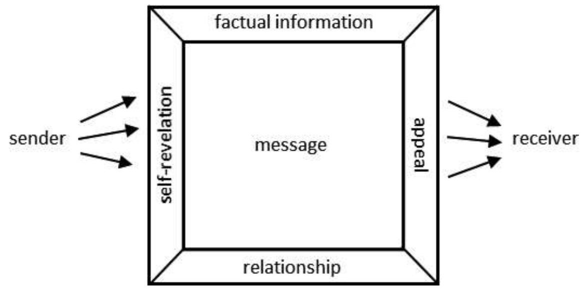

Figure 21, The four-sides model by Schulz von Thun [Eigner et al., 2014]

In terms of distributed work, communication is defined as understanding between task workers, generally as understanding between several people [Hoffmann, 2000]. Communication between employees serves the exchange of information and ideally concerns topics that are relevant to the work of both. The communication between employees influences their own work, but also the work of others, and due to the abundance of information mentioned above, which goes far beyond verbal exchange, there is a high risk of misunderstandings and confusion. According to Reichwald et al. [2000], human communication as a crucial component for the future of the workplace, organizations and markets. Especially in interdisciplinary product development teams that require a high proportion of communication to work effectively, a high degree of social understanding, empathy and knowledge are necessary to eliminate any risk of misunderstandings during communication. In conclusion, an identical level of knowledge of all those involved is necessary for optimal effectiveness in distributed development [Grieb, 2007].

A number of important obstacles are still in place which prevent effective collaboration between disciplines, following the consolidation of communication and cooperation for the development of products. Negotiating various terminologies [Tran et al., 2019], conceptual frameworks [Zheng et al., 2018], and goals across industries like engineering, marketing and manufacturing is a major difficulty. Lack of a common understanding, misunderstandings become simple to produce [Stock et al., 2021] [Enrique et al., 2018] [Senapathi et al., 2018]. Different perspectives can be generated by techniques like design background, but finding common ground necessitate constant communication and documentation [Liu & Lu, 2020].

4.1 The Human Factor and Teams in Interdisciplinary Product Development

The human factor

Since people are the primary focus of communication, it is important to first investigate and clarify the human component in the workplace. Product development is in a time of change through the implementation of mechatronic products and the announced fourth industrial revolution, that is why a variety of new approaches, theory and practices occurred. During this change companies have to find, adapt and implement the right tools and process models [Neubauer et al., 2012]. In practice, the responsible developers must eventually work with the IT solutions, and they have to integrate the newly developed procedure models into their existing workflow.

The processes of product development are driven by people who work individually and in cooperation with others as effectively and efficiently as possible towards a common goal. The decisive difference when considering human factors in contrast to all other factors in product development, however, is the self-dynamics of people. Even in a team-oriented product development, all team members have their own goals as individuals that they follow. This is an assessment, particularly in multidisciplinary product development projects when at least three distinct departments collaborate [Lindemann, 2009]. Human factors are therefore characteristics and behaviors of people in work situations. To develop an appropriate corporate culture during the application of a new corporate practice, employees must be able to understand innovative methods, processes and IT solutions. Moreover, employees must be motivated by the corporate culture to accept these new solutions and to integrate them into their routine activities [Lindemann, 2009].

In order to enable a successful development, it is advantageous to break down the complexity in the first step, because the human brain has a limited capacity and is therefore only able to process networked and complex skills to a limited extent [Lindemann, 2009]. The realization of phases of product development by developers depends on multiple factors of used and processed information. An effective use of this information by developers may be examined by the model of the information clusters. In this model, developers alternate between the five partial models "knowledge status", "target model", "problem model", "development model" and "verification model" [Lindemann, 2009].

The knowledge status is the sum of the developer's knowledge, experience and available information and findings which enables employees to access and search databases for necessary information. On the one hand, specialized expertise is needed in the area of interdisciplinary product development. In contrast, experiences in the product development process should also be available to simplify the complexity and to avoid making errors. The target model describes the current knowledge of the objectives in development which meet all the initially defined requirements, but these are often dynamic and change over the development process [Lindemann, 2009]. The problem model includes the individual and thus subjectively formed view of a problem. This aspect is particularly relevant for interdisciplinary product development since each department interprets the existing problem differently [Lindemann, 2009]. The development model represents the current state of development by means of CAD models, circuit diagrams, parts lists, etc. It is substantiated, improved and completed in every work step, whereby the complete development process is documented. The verification model supports solution analysis and knowledge acquisition, whereby the primary goal is the increase in knowledge and not the actual further development of the development model [Lindemann, 2009].

In industrial practice, particular too little attention is often given to the problem model, which results in serious consequences, especially in multidisciplinary development [Lindemann, 2009]. The clarification of requirements is not executed in sufficient detail and the various departments use it to form their own subjective interpretation. This is followed by a quick solution finding of the participating disciplines based on a development model. Only in the system integration of the subject-specific solutions generates an understanding of the actual requirements for the product. The information cluster model is intended to underline the importance of adequately clarifying the problem.

Human aspects and ergonomics have a vital but often overlooked role to play in the transdisciplinary creation of products, and their production. As usual, the areas of industrial engineering, operation and management focus on system performance and efficiency and ignore human factors [Battini et al., 2011] [Sgarbossa et al., 2020]. It is possible to simultaneously improve employee productivity, quality and results by considering human capabilities, limitations and well-being during the creative process [Battini et al., 2011] [Sgarbossa et al., 2020]. This requires interdisciplinary collaboration and human-centered techniques [Neumann & Dul, 2010]. Therefore, Industrial engineering, operation, design, mental health and business administration must work together to enhance the human productivity in the organizations [Sgarbossa et al., 2020].

To increase accuracy, statistical methods need to take into account human characteristics, including fatigue and age-related decline [Jaber et al., 2013]. Complementary measures are needed because management approaches must together optimize the effectiveness of the system and the well-being of individuals [Neumann & Dul, 2010]. Emerging Industry 4.0 technologies must be deployed while carefully considering their impact on employees [Kadir et al., 2019]. While robotics and technological advancement are rapidly changing business processes, current research focuses on the innovations themselves rather than their impact on humans [Neumann et al., 2021]. As previous industrial revolutions have shown, ignoring people issues generally has a negative impact on individuals and organizations [Neumann & Dul, 2010]. The effective use of Industry 4.0 requires the integration of human factor in all industries. One proposed approach is to methodically examine how the cognitive, physical and psychosocial variables of different people are affected by technology during the system's life cycle. The interplay between technology, human factors, mental health and leadership is necessary for these people-addressed approaches [Boudreau et al., 2003].

Teams

When it comes to product development, Ehrlenspiel [2007] defines a team as several people who work together based on factual or procedural considerations and deal with a common task in a goal-oriented manner. Similarly, according to Lindemann [2009], a team is a temporary working group that often clarifies certain problems, develops solutions or fulfils certain tasks as part of an overarching goal. In general, developers work alone most of the time, but decisions are often made as a team in critical situations that have a far-reaching impact and a high importance for the development process to be successful [Grieb, 2007]. The improved information sharing, the usage of synergistic effects, and resulting improvement in production are the economic principles behind teamwork. There is no universally accepted solution to the question of the ideal team size since team size has a significant impact on a team's effectiveness. To achieve the desired synergistic effects, a certain lower limit must be followed, and in order to avoid excessive communication effort, a set higher limit is also crucial.

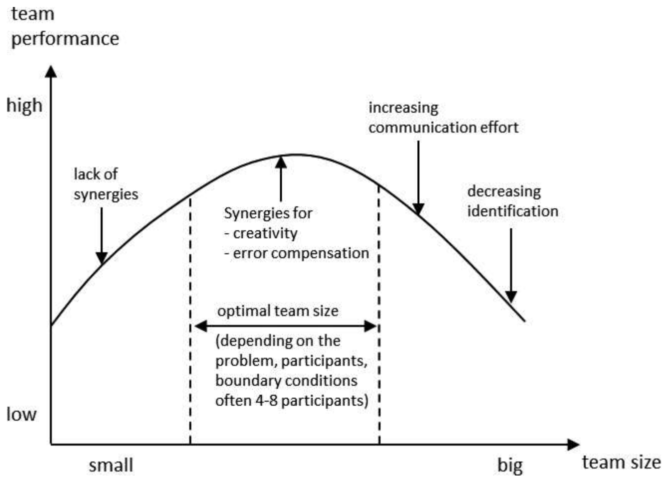

Figure 22, Team performance in relation to team size [Lindemann, 2009]

Figure 22 presents an exemplary relationship between team size and team performance [Lindemann, 2009]. The misunderstanding in a development team can be reduced by correctly carried out teamwork. An effective teamwork can be improved by increasing of the discursive communication and improvement of an overall understanding of the requirements instead of the self-interpretations of the individual disciplines. Furthermore, if team members are located in different countries the electronic forms of communication can be performed such as global virtual teams. However, an effective communication and knowledge transfer cannot be provided simply due to the different cultures and missing trust of the team members that cause misunderstanding and conflicts during the communication between team members.

The ideal size of team that affecting to team performance realize that, too tiny groups might not have the synergy and variety of viewpoints required for imaginative problem-solving, despite the reality that there isn't any agreement on the right size due to several factors at issue. However, large groups have difficulty organizing themselves and require more interaction. As additional knowledge and perspectives become accessible a larger team usually performs better at first [Malik et al., 2021]. Beyond a certain level, nevertheless, benefits start to decline as expenses for coordination rise and also cohesiveness deteriorates. The ideal team size will change based on the activity's amount of detail, the diversity of the organization's members, and the dialogue style. Groups with a lot of diversity and significantly interconnected duties typically peak at smaller sizes [Malik et al., 2021].

4.2 Formal and Informal Communication

In the literature, communication is often divided into formal and informal [Neubauer et al., 2012] [Kandlousi et al., 2010] [Dăneci-Pătrău, 2011]. Formal communication is impersonal, process-oriented [Ryu, 1998], and usually follows a well-defined task [Neubauer et al., 2012]. Especially in companies with a classic vertical hierarchy, communication occurs only in one direction and is therefore quick and efficient. Little requirement of coordinating and ensuring is an important advantage with clearly defined tasks therefore a short, described E-Mail is sufficient to convey the necessary information. Besides that, formal communication largely pursues a specific task, such as gathering information for a task to be done or forwarding information to the next process step. This type of communication is suitable for standard situations and routine activities [Neubauer et al., 2012]. However, one-way communication and routine activities with a purely vertical hierarchy don't correspond to functioning of product development, so that formal communication should play a secondary role compared to informal communication.

The creative process is at the core of product development, which is to receive a certain framework and order by means of process models. However, the actual creative process in which new ideas and innovations are developed remains disordered. This corresponds to its nature and can be promoted through informal communication. Informal communication takes up a third of all activities in companies every day. For companies engaged in PD, this proportion is even higher due to the creativity required in the process [Neubauer et al., 2012]. Informal communication describes the interaction of people without leadership and is mostly restricted not only on issues of the workplace, for example, a short brainstorming during lunch break, a conversation with the colleague from the other department while driving to a company event. Such a free discussion can create new ideas for products or unconventional solutions to problems. Information exchange has to be provided without restrictions in order to collaborate effectively and establish a creative environment. In addition, supporting the collaborative execution of tasks and the transfer of culture in the company [Whittaker et al., 1994], and also building up trust in each other are important factors for communication and the choice of communication channel for colleagues who do not work in close proximity to one another [Neubauer et al., 2012].

In summary, informal communication is the critical success factor for efficient product development and positively affects the processes used during product development. However, certain barriers can hinder informal communication. Whittaker et al. [1994] defines informal communication as purely personal communication, with the first barrier being the local distribution of teams. The number of communication tools has changed significantly throughout the last decades and the world is more networked than ever, but informal communication continues to take place almost exclusively in person, as it is unplanned and spontaneous. Another barrier is the refusal of informal communication, that may be caused by a variety of factors, including a lack of trust amongst employees or a corporate culture [Détienne, 2006]. Furthermore, the lack of a common grounds of knowledge, which can occur particularly in interdisciplinary product development, is another hindrance. If involved team members from different disciplines have a lack of holistic consideration or intended basic understanding of the thinking, misunderstandings can often occur. In addition, Denger et al. [2010] determined that there is an awareness of informal communication in practice. Problems arise, however, from the supposed lack of IT support and the incorrect use of existing communication technologies [Neubauer et al., 2012].

Since the team members originate from all departments and approach their development responsibilities in various ways, the formation of shared grounds of knowledge is a crucial component of multidisciplinary PD. To achieve this common basis of knowledge, the initial communication in an interdisciplinary product development team is necessary and should take place especially between an expert and a layperson. Especially in the use of technical terms is to check whether they are used and understood correctly [Feith, 2013]. Another approach for the establishment of the necessary knowledge basis is a collaborative process, which means that all developers involved must contribute their current knowledge of the project such as a rough overview of the most important key points and basics. This information exchange usually takes place through formal communication in order to bring all developers to determine future objectives and the project's current status. However, informal communication can support to fill information gaps that have remained despite extensive discussions. In many cases, a lack of knowledge may result in serious design problem that have to be resolved at a high cost [Détienne, 2006].

4.3 Communication Tools and Technologies

Computer-supported Cooperative Work (CSCW) is an expression that encompasses the study of how individuals collaborate in groups using the technology that allows for computer connections, as well as related hardware, software, services, and methodologies. [Schlichter et al., 2001].

CSCW is not only limited to communication tools, but the majority of cooperative work consists of information sharing that is necessary for communication and therefore CSCW can simplify human and organizational components of KM. Communication tools for KM in engineering encompass a variety of themes, for example, providing distributed communications work, solution for knowledge capture, encoding and organization, moreover, development of new technologies to support automation of design processes [McMahon et al., 2004]. These topics are especially important in an interdisciplinary product development since team members mostly work in different departments and therefore working in the same place is most of the time not possible. This leads to the need for appropriate and sophisticated communication tools and communication networks. Although traditional media, for example, over the phone, fax and in person keep their place in distributed development processes, because of the ever-increasing capacity of the Internet, computer technology and the growing integration of information technology will lead to the possibility of completely replacing conventional media in the future [Schueller & Basson, 2001]. For example, according to Qi et al. [2021], successful product creation employing the digital twin strategy requires seamless and real-time communication among the real item and its digital twin. As noticed by Qi et al. [2021] and Marion and Fixson [2021], this calls for a variety of communication technologies and methods.

For the computer-generated image to reflect its actual counterpart in real-time, sensors and Internet of Things devices must first be applied to gather actual information from physical objects and communicate it to digital twin simulations [Qi et al., 2021] [Marion & Fixson, 2021]. Second, various sources of information and processes are combined into a digital twin with the use of communication layouts, rules and industry norms [Qi et al., 2021] [Marion & Fixson, 2021]. To acquire knowledge, users may loose themselves in the digital twin environment thanks to human-computer interaction technologies. Along with connecting items, info and mechanisms, cloud platforms and industrial internet platforms also offer enhanced capabilities for analytics using digital twin data [Qi et al., 2021] [Marion & Fixson, 2021].

The selection of appropriate tools, their adaptation and integration into the development process are now crucial responsibilities for the companies due to the variety of technical systems. To understand this situation and select the best communication tools, a classification of these systems is necessary. Various approaches and models for categorizing groupware are available in the literature. In this section, following three best-known classification systems are presented to understand the features of the communication media and their applicability to assist the distributed product development:

- The space-time matrix according to Johansen [1988]
- The functional application classes according to Ellis et al. [1991]
- The 3K model according to Teufel et al. [1995]

4.3.1 The Space-Time Matrix

In this approach a 2x2 matrix is specified, as demonstrated in Figure 23, with the dimensions of time and space in order to differentiate groupware into four different classes. The time axis distinguishes between systems that support communication between partners synchronously (at the "same time") or asynchronously (at "different times"). The space axis differentiates between “same place” (personal meeting) and “different place” (electronic meeting) [Johansen, 1988] [Grieb, 2007].

	synchronous	asynchronous
same place (personal meeting)	e.g., conference room technology	e.g., message board
different place (electronic meeting)	e.g., real-time computer conferences	e.g., email system

Figure 23, Space-time matrix based on [Johansen, 1988]

For example, an e-mail system primarily supports asynchronous communication at different locations, while a real-time computer conference mostly provides synchronous communication at different locations. Conference room technology provides synchronous communication at the same location, whereas a message board serves asynchronous communication. A key point of this matrix is that several groupware systems can be assigned to several quadrants. Therefore, even choosing a comprehensive tool, all four quadrants should be fulfilled [Grieb, 2007].

4.3.2 Application Classes

A subdivision is presented according to functional application classes by Ellis et al. [1991], Schlichter et al. [2001] and Tippmann [2009]. They make distinctions between coordination systems, agent systems, conference systems, electronic meeting rooms, group editors and messaging systems. Although this classification approach also intersects, many systems can be easily classified in these categories according to their original and individual use.

Message Systems

Asynchronous exchange of information is the foundation of message systems like E-Mail. Main development goal of this system was communication between a sender and one or more different recipients [Gross, 2003]. Initially these systems were used only for text messages, today's systems also enable the exchange of graphics, images, sound and video. Message systems for the synchronous exchange of information have established in the form of chats or instant messaging systems. These synchronous systems enable written communication in real time and are getting more and more involved in companies [Kaiser, 2001] [Grieb, 2007]. Today's chat applications often have additional functions such as contact lists, status displays (availability) and file transfer functions.

Multi-User Editors

Multi-User or group editors allow group members to work synchronously or asynchronously on the same file, for example, spreadsheets and whiteboard applications. The editor is explicitly designed for this multi-use and does not isolate users from one another. A specific reminder system keeps all participants informed about the changes that are taking place and keeps them up to date.

Electronic Meeting Rooms

Meeting rooms are equipped with computers and projectors in order to visualize information for participants and thus to achieve a better understanding. These computer systems serve as tools for a decision structuring, presentation and analysis of results.

Conference System

Conference systems offer a wide range of interactions between meeting participants and two types of interactions are distinguished between group members that are real-time and non-real-time conferences. Real-time conferences require the full attention of everyone involved, since, information is exchanged in real time, which enables a quick exchange of information. Chats are the least informative type of real-time conference. The effort is low, and information exchange is quick, but the risk of misunderstandings is high. Compared to Chats, the videoconference provides more informative way, since participants are able to make out physical gestures and facial expressions in addition to the voice, however, this type of communication requires the highest organizational and technical effort. They also provide a lot of contextual information, as objects, people and events are visible in the recording area [Kaiser, 2001]. In non-real-time conferences, team members communicate asynchronously on their workstation.

Shared Information Space

Providing common information spaces for a group is main focus of this system. The processing and particularly the management of organized documents and information is a key aspect of group work. They enable the storage of data for additional time in an appropriate form and provide suitable access mechanisms (hypertext systems, multi-user databases, etc.) [Grieb, 2007]. There are various ways to manage the files, the distinction is usually defined by the way in which they work together such as separate responsibility, mutually exclusive access and synchronous access.

Coordination Systems

The asynchronous activities of the team members must be managed and coordinated with the aid of various coordination tools to enable the team to succeed. These applications give users the option to create groups and try to imitate the communication patterns found inside a team or organization. These structures are used for coordination of work processes, e.g., as a workflow management system and often specified by the company organization and also include the different roles of involved members. In developing this system, the goal is to integrate all the necessary basic functions for communication to enable all required communicative processes of the members.

Digital Twin Environments

Collaboration on design, simulation, analysis and sharing of real elements and methods can be achieved using digital replicas. Distributed groups can simultaneously view and interact with the digital counterpart with concurrent access features. Design iteration is controlled using version control [Singh et al., 2021]. Direct feedback is provided by integrating sensor data from comparable physical devices. Digital twins can improve group surveys, assessments and making decision [Liu et al., 2021] [Singh et al., 2021].

Mixed Reality Spaces

By applying technological developments involving augmented reality and virtual reality, mixed reality combines the real and virtual worlds together [Rokhsaritalemi et al., 2020] [Alpala et al., 2022]. This enables local and remote teams to interact with digital models in a shared environment as if they were real-world objects. Pop-up dialogs, visual teamwork and design workflows are all supported in mixed reality environments. Seamlessly integrating tools, platforms and websites is a challenge [Rokhsaritalemi et al., 2020] [Alpala et al., 2022].

AI Assistants

Virtual agents and AI chatbots can provide conversational interfaces to use product experience and knowledge [Wan et al., 2020] [Vasiljevs et al., 2017]. They provide developers with the ability to query information and receive suggestions through voice or text interactions by combining domain knowledge bases and natural language processing [Vasiljevs et al., 2017]. AI can retrieve previous plans, claims, justifications and other artifacts to improve access to individual and collective knowledge.

Smart Infrastructure

"Smart" team spaces combine hardware, such as interactive whiteboards, wearables, sensors and spatial trackers, with software and cloud capabilities [Hassan et al., 2020]. As a result, intelligent and adaptive settings are created, suitable for a variety of creative tasks and team sizes [Lu et al., 2020]. Depending on how the workspace is used, knowledge capture and exchange can be automated. But there are barriers to adoption [Hassan et al., 2020].

Digital Thread Platforms

The digital chain connects data and communication exchanges across the whole product lifetime, from conception to usage and beyond. The integrated platform provides seamless end-to-end product knowledge while bridging the information gap between industries [Margaria & Schieweck, 2019].

4.3.3 Categorization Using the 3K-Model

The groupware or CSCW systems frequently facilitate group member coordination, communication or cooperation, therefore, in the 3K model the systems are assigned to their level of support for these three basic concepts. The decisive criterion for the assignment is the effectiveness of the support of the technology for the respective sub-process.

A triangle in Figure 24 presents the main idea of 3K model. Communication, coordination and cooperation are determined at the corner points of the triangle and the groupware systems are placed depending on the support function. Team members can exchange expertise and information through communication, in this category chat platforms such as Slack, HipChat, Telegram, Jabber, WhatsApp and web meetings e.g., Skype, Google Hangouts, Adobe Connect can be mentioned as internet-based applications. Coordination aims to support the distribution of resources and the coordination of independently workable tasks for team members. Outlook, Google Calendar, Asana, Trello, Dropbox, MS Project, Jira can be given as examples. Cooperative support, on the other hand, prioritizes the tracking and achievement of common goals by the synchronous processing of knowledge-intensive tasks. Tools for this support are, for example, collaborative writing (Google Docs, SharePoint) and groupware (Microsoft Exchange, Microsoft 365) [Schlichter et al., 2001] [Teufel et al., 1995] [Grieb, 2007] [Paul, 2018].

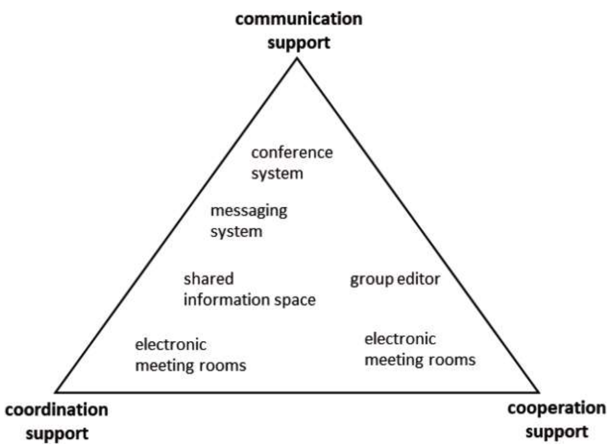

Figure 24, 3K-Model [Schlichtler et al., 2001]

As other classification approaches, this model may be also applied as tool and guideline for evaluating and selecting appropriate communication tools for the various activities that will be executed during a development process. However, a clear assignment is not always possible in this model either, because several functions are integrated in most groupware or CSCW systems [Grieb, 2007].

4.4 Summary and Assessment

Successful innovations are important for companies for the generation of a sustainable competitive advantage in the times of globalization. To achieve innovation in a multidisciplinary team a creative environment and collaboration without restrictions must be provided, because the sharing of information and knowledge is essential for innovation and creativity. The knowledge sharing is an unavoidable activity especially in the engineering design process since many tasks have to be accomplished according to knowledge from other areas of specialization. Therefore, the performance of product development depends on the communication and collaboration into the engineering design team. A shared aim can be provided, and creativity increased by communicating the right design intent and domain-specific knowledge to the proper employee at the suitable time in a communication or collaboration tool. In addition, the loss of expert knowledge, that can be occurred through the limited and non-goal-oriented communication, can be avoided with the application of acquisition methods through a knowledge integration in a communication tool.

The working conditions for product developers have changed significantly in recent years, for example, coordination and communication are taking more and more time, and leaving less time for actual development activities. Therefore, in this section, an overview with respect to human factor and his or her communication in the development teams is also provided. In product development teams, communication and the usage of appropriate communication technologies are crucial to work effectively with employees from different departments, countries and with different backgrounds. Misunderstandings in development departments can be very expensive, therefore, a high level of understanding is necessary to avoid unnecessary costs due to misunderstood information. In this respect, two ways of working for development teams are available. One option is to position everyone in a team nearby one another to improve opportunities for informal communication, therefore, creative brainstorming and problem-solving ability in development processes can be improved. The second option is the virtual teams which has been resulted through changed work conditions such as increasing interdisciplinarity. Virtual teams are intended to help the creative process by freeing team members from rigid organization and allowing them to work flexibly. However, for conventional teams, and especially for virtual teams, to provide efficient communication during product development appropriate tools and solutions must be found, adapted, introduced, used and maintained in their entirety. Therefore, in this section different approaches presented for the classification of a large variety of groupware systems to support distributed work. However, a consistent classification to define suitable tools for a specific task is complicated since existing systems are very different and often include several functions. Additionally, it is challenging to select the best course of action given the ever-increasing variety of tools at hand.

Three main classification approaches (the space-time matrix [Johansen, 1988], the functional application classes [Ellis et al., 1991], the 3K model [Teufel et al., 1995]) were presented for evaluating and selecting appropriate communication tools for the various activities that will be executed during a development process. Regarding to these classification approaches and product development activities some findings can be summarized for the groupware systems.

An important evaluation criterion for groupware systems is the passive or active sharing of information. For example, an e-mail system primarily supports asynchronous communication, and that is the main reason why it's an entirely passive transmitters of information. However, a real-time computer conference mostly provides synchronous communication. In this category, the active information and knowledge transfer between team members is propped up by various internet-based applications such as Slack, Telegram, Jabber. Moreover, web meetings e.g., Skype, Google Hangouts are also synchronous tools which are well suited for supporting distributed product development that needs mostly a long meeting. Furthermore, video and voice conferencing are also used for collaborative work in many companies and is suitable for complex tasks in a development process. If a high-speed digital communication is available, besides voice and video conferencing participants can also work simultaneously on a shared whiteboard for the collaborative writing and drawing. By means of remote screen sharing tools, e.g., SharePoint, Microsoft Exchange, Microsoft 365, knowledge-intensive tasks can be processed synchronously in order to accomplish shared goals. These are technologies that have already been used to support and aid significant product development processes in an enterprise. However, in terms of knowledge management generation, incorporation and sharing of knowledge in any appropriate groupware system can bring major advantages to support decision-making and idea generation during development activities which is also defined as main goal of this work.

5 Concept

In recent years, communication has become an essential part in the success of a business since employees in business processes spend a considerable time on tasks that require coordination and collaboration with other employees. In order to improve this interaction between employees, especially remote work, digital communication software has to be adopted in companies for the achievement of company goals and finishing the project on time. Due to this, the concept of the knowledge management and communication platform, which is the main objective of this study, is briefly described in this section.

The first part gives a short overview about potential stakeholders for the aimed knowledge management and communication platform. Team members in a development process are in fact knowledge sources in the knowledge management and communication platform. Right team members or users are able to acquire and capture knowledge internally and externally through variety of communication tools. Therefore, it is crucial that the stakeholders and potential users who will directly interact with the communication tool have to be identified.

Secondly, the main concept is described regarding a use case scenario that is adapted from Henrich & Morgenroth [2006] (see further details in section 2.4). In this scenario the principal idea of the current work and the proposed communication platform is presented. Furthermore, development of a 3D Printer is considered and explained in order to comprehend how a DfX-based platform for KM and communication support for the decision-making processes of developers throughout the initial stages of product development.

Thirdly, main system components, software architecture with a Java Model-View-Architecture and software technologies for the system development are going to be presented. Basically, the communication component together with knowledge management component, which is the core component of this platform, provides generation of knowledge, a query and a tagging mechanism for the managing and maintain of the demanded knowledge. The storage component stores previously acquired knowledge from finished projects as well as recently acquired knowledge in line with DfX, moreover, messaging history, data about user and their roles.

Finally, development of a 3D printer as an example product that is manufactured in the pilot factory will be highlighted since a realistic use case can provide better understanding and can assist for defining the concept of communication platform in more detail. Moreover, a realistic application environment may be available by using 3D printer for the development of the communication platform. In this section a general ontology for a product is going to be also presented to give an overview about the knowledge representation and use. With regard to the idea of communication platform, the use case of 3D printing development as an example product will be explored. This is related to functional components, manufacturing methods, resources and DfX-aspects. Additionally, five DfX categories, along with their subcategories, are evaluated and defined based on the literature. These categories are used for generating and storing knowledge within a hierarchical structuring approach for the implementation of the prototype.

5.1 Stakeholders

Nowadays, the ways employees collaborate and communicate at work on projects is improving across countries and time zones. Therefore, the demand for communication platforms and software is indispensable particularly for the elimination of problems in development projects such as uncertainties, unclear goals, poor coordination, ineffective decision-making process. Effective collaboration and connection by using the right communication tool enable employees as well as clients and partners to realize successful outcomes. However, every company has to consider needs of their teams that works mostly unique for each company. Some requirements can be, for example, providing the appropriate information to the appropriate team members at the appropriate time to prevent time wasting activities for the finding the information. Moreover, supporting employees with right information during real-time or asynchronous communication can simplify the way employees work and improve quality of work.

A good understanding and defining of stakeholders are important for the implementation of a communication platform for the development teams in an enterprise, but it is equally important to create right team for a project throughout project lifecycle. These two aspects are significant for a company; however, users being taken into account as stakeholders in this proposed knowledge management and communication concept is main focused. Individuals can be internal or external stakeholders who are involved, for example, in a product development project. Users such as employees, customers, supplier and authorized partners can acquire and capture knowledge in the communication platform. Knowledge can be generated internally through real-time conversations between employees, for example, not only in a research or development project, but also in corporate instruction and learning activities. Externally generation of knowledge may be realized, for example, through cooperation and communication with clients, suppliers, as well as users of products. For the establishment of a collaborative knowledge management, first of all, stakeholders who may access and use the system have to be clarified. In this concept, internal stakeholders of knowledge management and communication platform are development team and also colleagues of other departments, such as management, logistic, quality, etc. In another words, any individual inside the business who has an idea can be a potential actor into our concept. External stakeholders for our concept can be defined as partners in engineering or development, suppliers and clients.

5.2 A Potential Scenario for an Engineering Team in the Proposed Knowledge Management and Communication Platform

The major objective of this work, as described in earlier parts, is to establish a knowledge management and communication platform based on DfX to assist development engineers and teams during decision-making processes. Moreover, this concept makes the gathering and connecting of acquired knowledge available through a scanning or keywords extraction process in accordance with DfX principles during the early phases of product development. Therefore, implicit knowledge of experts can be acquired and maintained in a systematic manner, and subsequently the gathered knowledge from finished projects can be shared and used effectively through communication platform.

Figure 25 presents and explains the primary concept of the current work using a scenario that has been adapted from Henrich & Morgenroth [2006]. Henrich and Morgenroth mainly focused on the use of important DfX criteria for the fulfilment of the targeted search for documents within a project that may be relevant. Compared to Henrich and Morgenroth, the main concept of this work is clarified in below presented scenario to understand how design intent and domain-specific knowledge can be generated, stored and used while the stakeholders collaborate and communicate tasks related to development for the current project.

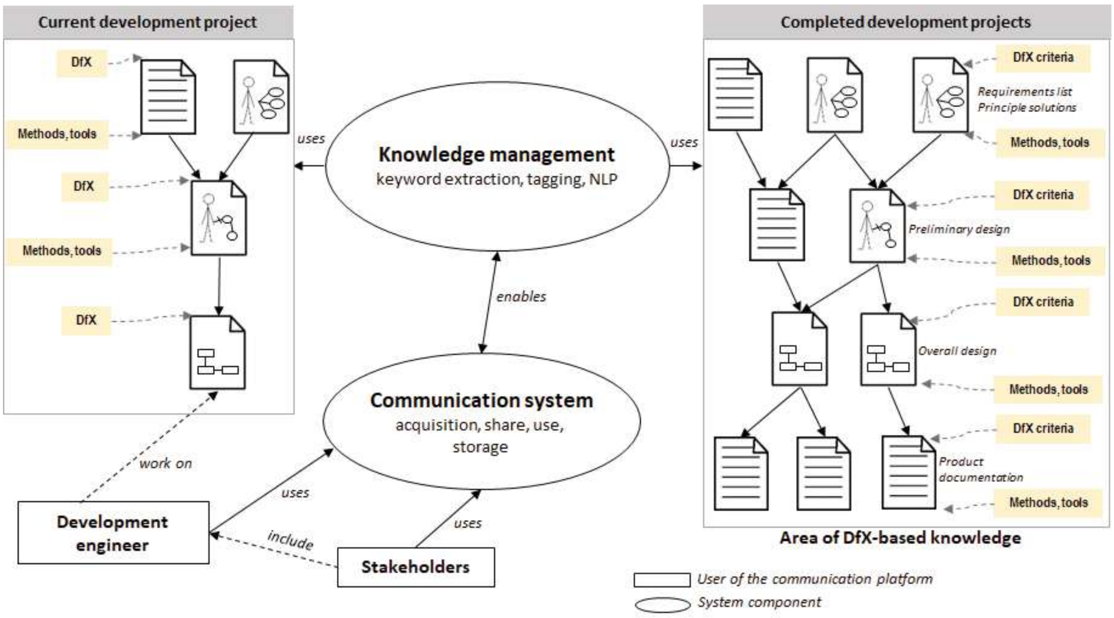

Figure 25, The knowledge management and communication system's fundamental idea modified from [Henrich & Morgenroth, 2006]

To understand the fundamental principle behind this idea in Figure 25, the primary elements of this system, namely communication, knowledge management, and area of DfX-based knowledge, will be next clarified. Basically, the communication component aims, on the one hand, to provide a systematic identification and acquisition of the relevant explicit or implicit knowledge while stakeholders communicate and, on the other hand, to assist with the usage of acquired knowledge from previous projects for the stakeholders. During collaboration and communication of users, knowledge management component enables generation and storage of context specific knowledge in a structural form by using key words in the field of DfX-based expertise for additional usage in upcoming projects. Furthermore, the knowledge management component supports acquisition and presentation of knowledge in the communication system by means of a scanning and tagging mechanism. In this context, the knowledge management component also acts as a bridge between communication and area of DfX-based knowledge.

For a deeper comprehension of the idea, the scenario that is being provided will be discussed by a 3D printer development use case that will be described in section 5.6. In this situation, the development engineer and team are aware of the requirements, fundamental idea, applied techniques and tools. The development engineer starts working on a general design and uses a communication channel to interact with other stakeholders. If development engineer needs important DfX-based knowledge to ensure a decision, a query can be applied by development engineer in the communication and knowledge management system to find right DfX-based knowledge for any task in the overall design. This query option is also available for stakeholders without participation in the communication. In the next step, DfX support in presented scenario will be determined based on the 3D printer example. Assume that some design information of the 3D printer comes to the fore and this information is directly related to DfX rules. For example, XY- and Z-Belt tensing system as well as drive shaft must be improved throughout the product creation stage for the purpose of improving the use case for 3D printers. For the development of a quick and simple assembly operation (Design for Assembly), a new belt tensing system that is a more static part in the form of a Z profile with slotted hole will be replaced by an L profile. Moreover, the improvement of the 3D printing stability and accuracy (Design for Quality) can be provided by using a steel tube drive shaft instead of an aluminum shaft. In summary, development activities with respect to DfA and DfQ are the main focus for the optimization of 3D printer during development processes that moment. That is why the knowledge management system aims to achieve acquiring and storage of required knowledge regarding DfA and DfQ by means of specific keywords such as "extrusion temperature, layer thickness, missing layer, printing accuracy, surface quality", which are actively communicated and discussed in the communication platform. Additionally, when it involves incorporating and communicating DfX-based knowledge of DfA and DfQ into other and upcoming development projects, developers and stakeholders are assisted with the stored DfX-based knowledge by using the similar keywords like printing accuracy, surface quality, missing layer during the active communication about a new design, for example, the belt tensing system of the 3D printer.

5.3 Software System Architecture

Access, a knowledge management component, and storage can be regarded as the three main system components of the suggested framework in Figure 26. The access component as a knowledge portal provides a conduit connecting the system and users, moreover, serves a web interface where members of a knowledge community can enter in the system.

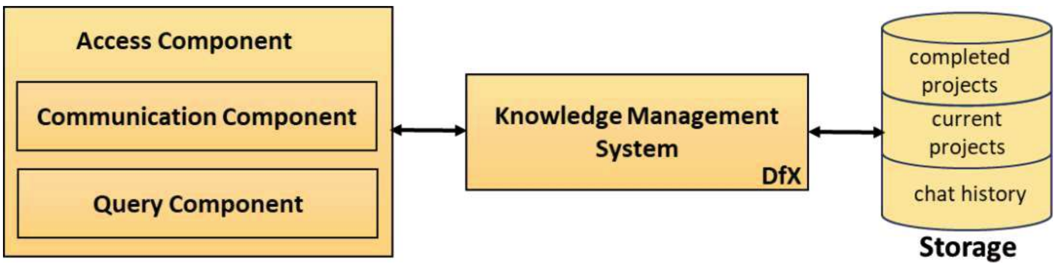

Figure 26, The main knowledge management system components

The knowledge portal's communication component seeks to facilitate rapid information exchange as well as synchronous message or chat functions. Furthermore, the communication component is designed for acquisition and storage of knowledge through knowledge management component based on DfX aspects. Besides communication component, the query component assists knowledge users with queries through the knowledge management system to find relevant knowledge within the context of DfX and product development task. User can apply related keywords in the query mechanism to rich context-based information in various form, for example, knowledge definition, knowledge artifacts, documents and pictures. The knowledge management component is the core part assembled with other elements to fulfil requirements of the aimed knowledge management and communication platform. Moreover, this core component has to connect and communicate with access, storage and other components so that specific needs and functionalities of the proposed concept can be satisfied, for example, scanning the messaging activities through a tagging mechanism or keywords extraction subsequently storing acquired knowledge in the DfX based knowledge repository. The storage component contains basically databases for the knowledge from finished and present projects as well as chat history, user data and roles.

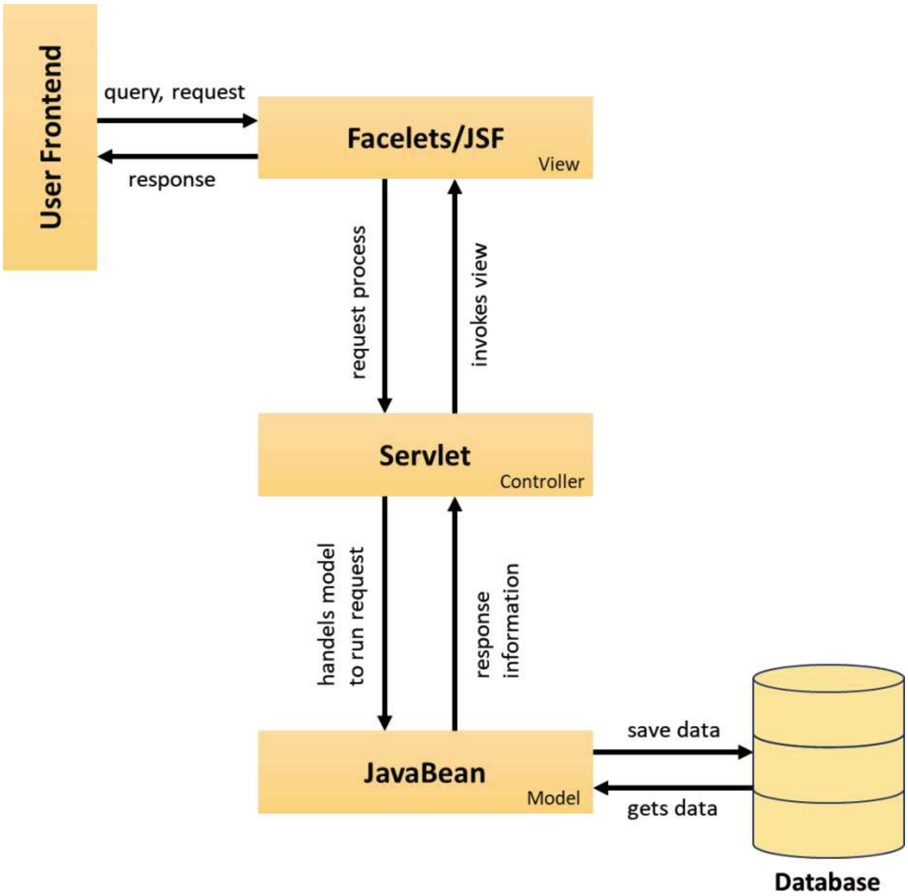

Figure 27, Model-View-Controller architecture pattern

The MVC (Model-View-Controller) software design pattern in Figure 27 is used to show how the intended knowledge management and communication application is designed, moreover, how the using software technologies interact and work each other. The presented common Java MVC framework is divided into three components that are model, controller and view. These connected parts are used to develop user interface (UI), control logic and data process. The model component of the design pattern stores and manages data that is not displayed to the user, however, this stored application information processed separately from the user interface. In fact, the model element of the built application presents and stores all of the data and pertinent logic that the user interacts with. Data can be saved in the database and retrieved from it at the controller's request since the model has a connection to the database. The view component provides the user interface of the communication platform for the stakeholders to access and see the information that is collected by the model part in the application. The controller component of the application builds a bridge between model and view, therefore, interaction of user with the system can be handled. Inputs of the user from the view component are received by controller that converts the request by using designed logic to a command for the model. Basically, after receiving and update of data in the model, data is handled and manipulated through controller upon the user’s request from application to browser back for the display of final output.

An example (with 3D Printer) based on DfX principles can be used for understanding of the working of MVC software design pattern. At first end-user is able to access into the knowledge management system via the query option or by participating in the collaborative communication interface which is connected with User-Frontend. If a request such as “printing accuracy” is submitted, the view component which is supported by Facelets/Java Server Faces (JSF) processes the request that can be a query or a detected keyword through scanning assisted by NLP. In this case, the processed keyword that is applied for a classification of the knowledge according to the DfX aspects can be used for both knowledge acquisition and knowledge use. The controller component that is assisted by a Servlet interacts with the model and invoke the logic to run request for getting or saving related data. Based on the request or query data the model JavaBeans connects to database to save data regarding with DfX and detected Keyword. Moreover, the model provides a request to fetch the necessary data from DfX based database and answer back to the controller. The information derived from the model by means of DfX and “printing accuracy” request is submitted then the view component. The view displays the needed information from model based on current request to the end user.

5.4 The Connection of Knowledge Subjects and Processes Based on Development of a Product with DfX-Aspects

To understand the relations between potential knowledge subjects, processes and DfX-aspects, a general ontology of components related to a product is taken into account in context with the knowledge representation, storage and use. Moreover, how the spreading knowledge particularly with regard to product development can set a goal to receive the context-based knowledge to the right person in an organization. Therefore, Figure 28 presents a product that is linked with functional elements, production techniques, materials, and associated DfX principles which clearly shows us that knowledge can be available from any linked component or source. The main knowledge source is individual that can participate in a virtual or global organization and can share his or her explicit or implicit knowledge. Moreover, technologies and standard parts which are used for development of the product are also connected.

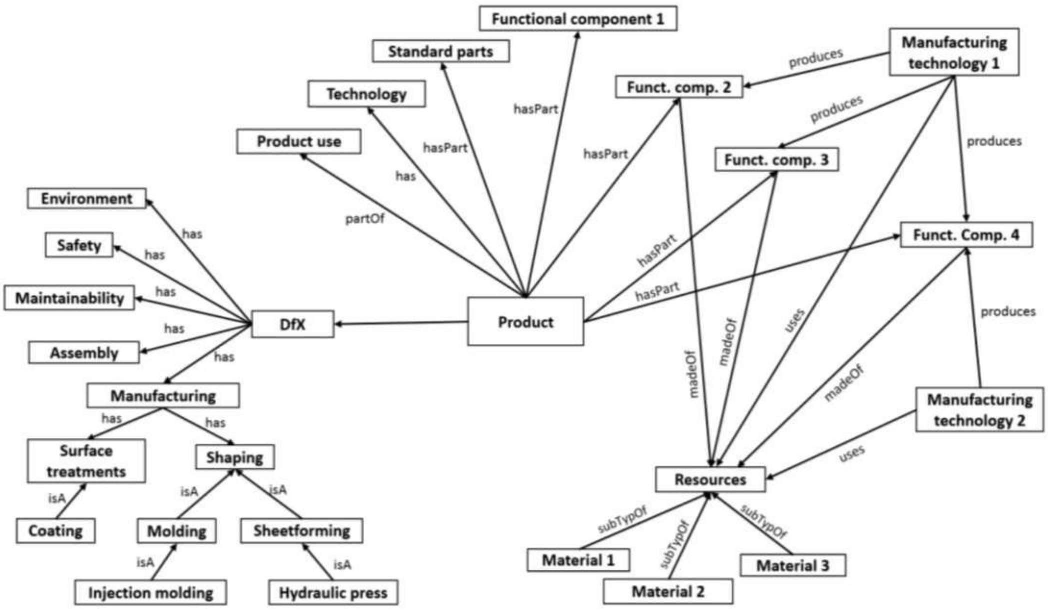

Figure 28, Relation of knowledge subjects through development of a product with DfX aspects

In this context, the use case 3D printer can be adapted in the presented scenario on the basis of components which are involved in product development and production. The functional components for 3D printer can be defined, for example, driving shaft, extruder, heater, guiding block, print head, belt mechanism etc. Cutting, milling, turning, drilling and other machining processes are available for the manufacturing of functional components of 3D printer. For the production of functional components materials such as steel and aluminum can be intended as resources. As a knowledge basis to support processes for developing products with relation to DfX, categories including such as design for safety, quality, cost, assembly, maintainability and environment are specified. With the addition of DfX categories in Figure 28 the relation of connected knowledge elements and processes for a product can achieve a clear understanding of main purpose of the proposed concept that aims acquiring, storage and representation of knowledge according to DfX aspects. The relation between the potential keywords (explained in section 5.2) and DfX aspects can be closer considered according to presented figure with respect to 3D printer example. The surface quality and printing accuracy as keywords can be related to drive shaft, which is made of steel or aluminum. For the manufacturing of drive shaft, a lathe machining is provided. As a conclusion, the occurred knowledge within the product development processes may be acquired and stored through the relation between keywords such as surface quality, printing accuracy and design for quality (DfQ). Moreover, stored knowledge can be provided through a query or scanning mechanism by using of existing keywords to assist developers in order to receive and use relevant knowledge to make a right decision with respect to quality or assembly.

5.5 Definition of DfX Categories

One of the key objectives of the intended approach is to generate and store knowledge across DfX categories and subcategories in a systematic manner. To implement the prototype, five DfX categories are used in the first step. The agreed categories are Design for Manufacturability (DfM), Design for Quality (DfQ), Design for Assembly (DfA), Design for Costing (DfC) and

Design for the Environment (DfE). This section summarizes the subcategories and evaluates each category in relation to the literature. Hierarchical structuring approach is going to be applied for the determined subcategories. Furthermore, first level hierarchical relationships between different DfX aspects will be identified for implementation of the subcategories.

5.5.1 Design for Manufacturing

In the last decades implementation of DfM approaches and tools in the product creating stages has been improved as a meaningful topic to achieve a connection between engineering design and manufacturing. Due to development and integration of this connection existing problems regarding to manufacturing can be considered and improved throughout the first stages of product development. Using DfM, a product can be designed and developed by means of manufacturing knowledge that has been generated over all phases of the product life cycle so that production costs may be decreased, and product quality can be raised [Mattson and Sorensen, 2020] [Gebisa & Lemu, 2017] [El Souri et al., 2017] [Battaia et al., 2018]. To realize an efficient manufacturing process as a main purpose of the DfM, inefficient operations and excessive use of materials have to be prevented in design stages for minimizing the manufacturing cost and time [Ji et al., 2022] [Battaia et al., 2018]. However, achieving the aforementioned objectives is a difficult and knowledge-driven process for the development teams in the businesses [Ji et al., 2022]. To overcome this challenge, development teams have to take many aspects into account, for example, use of material, manufacturing process, complexity of operation, overall part production, using machine, tooling and also existing technologies [Battaia et al., 2018]. Therefore, establishment of a knowledge base for the numerous DfM aspects and principles to support decision making processes through avoiding manufacturing and quality problems is mandatory for companies to accomplish the reduction of cost and time in the design stage [Ji et al., 2022] [Doellken et al., 2021] [Battaia et al., 2018].

For long-term manufacturing process improvement, a DfX based knowledge management approach is applied in this concept to generate and store knowledge and experience of different manufacturing aspects and principles, moreover, use this knowledge in the product development process. In Figure 7 [Bauer, 2007] a hierarchical structuring of DfM which extended into different levels of detail is presented. To perform advantage of DfM concept important principles and guidelines for specific manufacturing processes, such as injection molding, coating, shaping, cutting, machining, or casting have to be available in DfM knowledge based for the engineering teams. Additionally, engineering teams must be supported with the necessary process knowledge during the beginning stages of product development including minimizing total number of parts, using standardize components, removing secondary operations and setting right tolerances [El Souri et al., 2017] [Mattson & Sorensen, 2020] [Doellken et al., 2021] [Gebisa & Lemu, 2017].

In conclusion, the strategy is intended to cut manufacturing costs and time during the initial stages of product creation with a KM and communication tool where manufacturing knowledge from the hierarchical DfM storage is provided by means of the communication platform within the overall organization. Moreover, new knowledge or experiences of engineers about manufacturing aspects can be acquired and managed by using this communication tool so that the engineering team can actively consider the most recent manufacturing knowledge when designing and optimizing the product.

5.5.2 Design for Assembly

For businesses to produce and optimize industrial products, early design consideration of assembly issues is crucial. For the reduction of costs in manufacturing process an efficient assembly process needs to be defined and implemented. However, complex analyses have to be performed since product complexity has been increased during last years. Moreover, designers don't address often assembly problems and DfA rules during designing a product, therefore, difficulties occur regarding assembly lead time [Melckenbeeck et al., 2020] [Cabello et al., 2018] [Aydinli & Özkaya, 2022] [Mattson and Sorensen, 2020]. Furthermore, products such as wind turbines and elevators must be designed and improved according to DfA aspects to ensure long life cycles [Remirez et al., 2019] [Battaia et al., 2018].

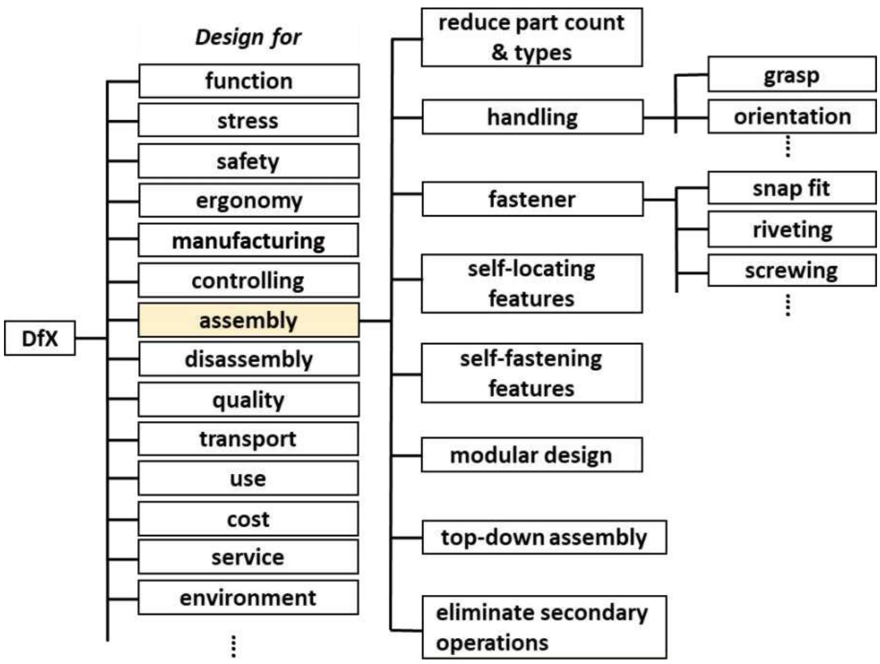

Figure 29, Hierarchical structuring of DfA

In general, engineering design process contains various working tasks that must be considered by designers with methods, rules and principles to achieve a successful design. Therefore, a hierarchical structuring of DfA aspects and principles in Figure 29 is defined to provide a knowledge base. The main issues with the assembly processes can be found and fixed at the design phase using an established knowledge base for DfA. During the design phase, the guiding principles for assembly operations must be taken into consideration. These principles include, for instance, using more of the same components, reducing the total number of parts and material diversity, creating modular design for a better handling, and providing integral fasteners [Battaia et al., 2018] [Bouissiere et al., 2019]. Moreover, other objectives of DfA can be reducing assembly directions, optimization assembly surfaces and minimize the number of operations in overall assembly. All these rules and principles aim to facilitate complexity of manufacturing process and minimizing assembly time as well as cost [Mattson and Sorensen, 2020] [Cabello et al., 2018].

In summary, innovative techniques and tools must be created to support designers in locating issues and enhancing the final product regarding to the assembly stage. Therefore, this research aims to provide a software that brings communication and knowledge management together since designers require right DfA rules and principles as mentioned above at the right time during design stage for the improvement of assembly process.

5.5.3 Design for Cost

In the initial phases of the creation of a product, several factors from other fields have to be considered to accomplish the targeted product costs. An optimized and facilitated decision-making process during product development can increase the effectivity of the multidisciplinary development team regarding to DfC for the reducing of product lifecycle cost. However, before costs can be calculated, the product's life cycle operations, like the manufacturing process, must first be understood, defined and evaluated. Otherwise, various iterations to DfC have to be performed since necessary knowledge on cost is not available mostly in a timely manner. To enable a significant reduction in product cost, designers must offer all necessary choices in the initial phases of product creation prior to manufacturing [Roy, 2003].

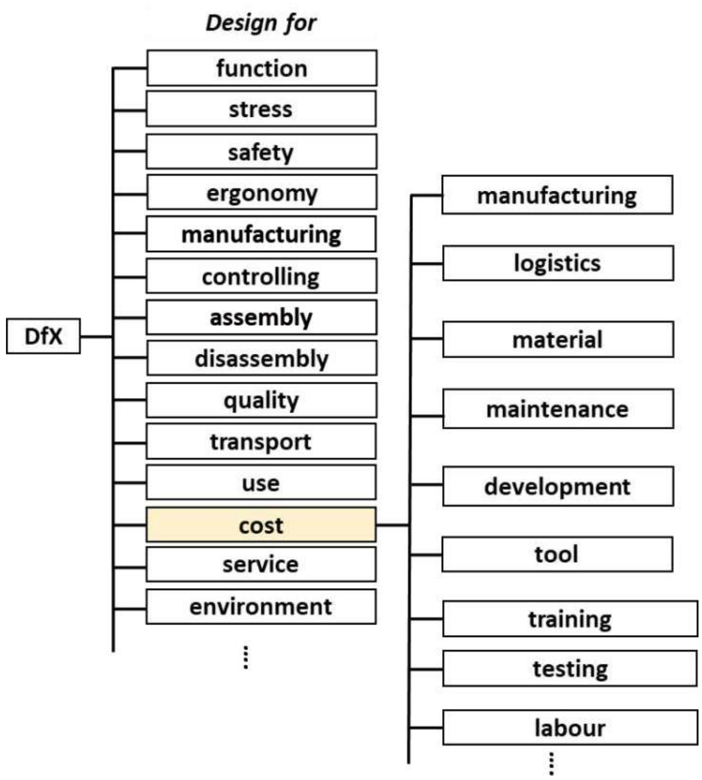

Figure 30, Hierarchical structuring of DfC

Figure 30 illustrates how the DfC categories cover a range of ideas and concepts that can be used to reduce costs while developing products. These principles and aspects can bring out a knowledge base that supports designers to perform an analysis of possible cost drivers. In order to achieve DfC analysis following aspects must be considered, for example, material specification and cost, development cost, manufacturing cost, the number of operations, equipment cost, logistics, packaging, testing, labor. Moreover, some important covered aspects impacting costs can also come forward in a project, for example, re-design, re-test and working on obsolete parts [Roy, 2003].

5.5.4 Design for Quality

In recent years, quality is not only valid for providing the required technical functions of the product, but also many other requirements regarding safety, ergonomic, reliability, serviceability, aesthetics must be fulfilled. The main purpose of this multifaced quality aspect is to satisfy customer's needs and expectations. If a company wants to achieve a sustaining competitive advantage, customer satisfaction as a key factor must be performed through identification and implementation of quality measures [Pahl et al., 2006] [de Meireles Carneiro, 2020] [Hoe & Mansori, 2018] [Stylidis et al., 2015]. In addition, companies need to generate innovative strategies to overcome difficulties in evaluating product features that impact customer satisfaction. To realize a successful product with a competitive advantage, a continuous improvement of customer satisfaction must be combined with a cost reduction. For the consideration of the product attributes depending on their own experiences and DfQ expertise, designers must therefore be involved in the process of designing products [Hoe & Mansori, 2018] [Stylidis et al., 2015].

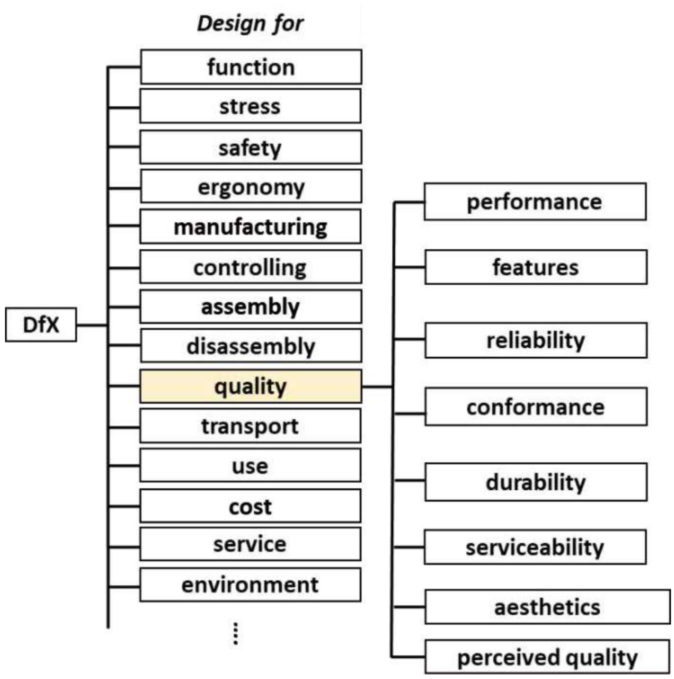

Figure 31, Hierarchical structuring of DfQ

To aid in the assessment of this multidimensional aspect of quality in the organizations, Garvin defined five approaches to assessing quality [Garvin, 1984] [Garvin, 1987]. These approaches are transcendent, specific to product, specific to consumer, specific to manufacturing, and specific to value. By taking the product-based approach, quality becomes a measurable quantity and focuses on understanding the customer's requirements. As a result, eight dimensions of product quality as seen in Figure 31 were defined by Garvin basic elements to assist producers to satisfy customer expectations trough analysis of quality aspects [Sinclair et al.,1993] [Stylidis et al., 2015]. The proposed product quality categories are durability, performance, reliability, conformance, features, serviceability, perceived quality and aesthetics [Hoe & Mansori, 2018].

As the first dimension, performance, describes primary operational characteristics of a product. Second dimension features are additional attributes that enhance performance of a product. Third, reliability indicates failure frequency of a product during its use. Conformance as a fourth dimension refers to fulfillment of the operating characteristics of a product to the specified standards. Durability relates to economic and physical product life that is also be considered with repairing. Serviceability is present for speed, ease and costs with that product can be repaired and serviced. Seventh dimension aesthetics is defined for the properties that product presents such as it looks, feels, sounds, tastes, etc. Final dimension perceived quality has similar characteristic to aesthetic since market positioning, images from advertising, and experiences can define attributes of product by customers, however perception does not always correspond to reality [Sinclair et al.,1993] [Hoe & Mansori, 2018].

5.5.5 Design for Environment

In recent years the environmental impacts of products have become a central aspect for the companies due to public policy, government regulations as well as consumer preferences. Therefore, product designers have to address many factors that influence the environment. The environmental impact of products has been considered like customer needs during the initial steps of product development to enhance better environmental performance for the decreasing of environmental footprints. However, satisfaction of essential requirements for the environmental sustainability with the purpose of high product quality and lower cost is a major challenge for the development teams. For this reason, various Design for Environment (DfE) methods and tools have been advanced in the past several years to aid designers in efficiently considering environmental aspects in the earliest development phases in order to create greener products [Telenko et al., 2008] [Lindahl, 2006] [Kolur et al., 2020] [Fitzgerald et al., 2007]. For instance, life cycle analysis (LCA) is currently the most extensively recognized and utilized method for analyzing the impact of products on the environment during the entire product life cycle. Indeed, implementation of LCA completely correctly requires detailed knowledge of the available products, so it is clearly complicated to implement in the beginning phases of product creation [Telenko et al., 2009].

As presented in Figure 32, DfE has a wide scope and includes many sub-categories, and each of them has numerous design specific guidelines, aspects and principles for minimizing or eliminating the consequences of a product on the environment during its life cycle. The main DfA aspects are, for example, reducing energy demand in the manufacture and use of products, minimizing emissions, reducing number of materials, eliminating hazardous materials and minimizing toxicity in the processes, optimizing packaging, reducing disassembly time and using recycled materials. Moreover, reusability, disposal, transportation, durability, regulations and standards are others important topics that must be addressed in the early design phase.

The selection of environmentally friendly materials is one of the critical dimensions to enhance a product's ecological performance. The choice of the right materials or material innovations have a massive effect on the environmental rating of the product due to recyclability, toxicity and end-of-life. Materials, for example, iron, steel, copper, aluminum, polypropylene, polyethylene, nylon, ABS, PVC, wood products and paper are recyclable and should be preferred at the design stage, whereas laminated materials such as plastic foam, galvanized steel, ceramics, thermosetting plastics are not recommended due to missing ability for the recyclability [de Meireles Carneiro, 2020].

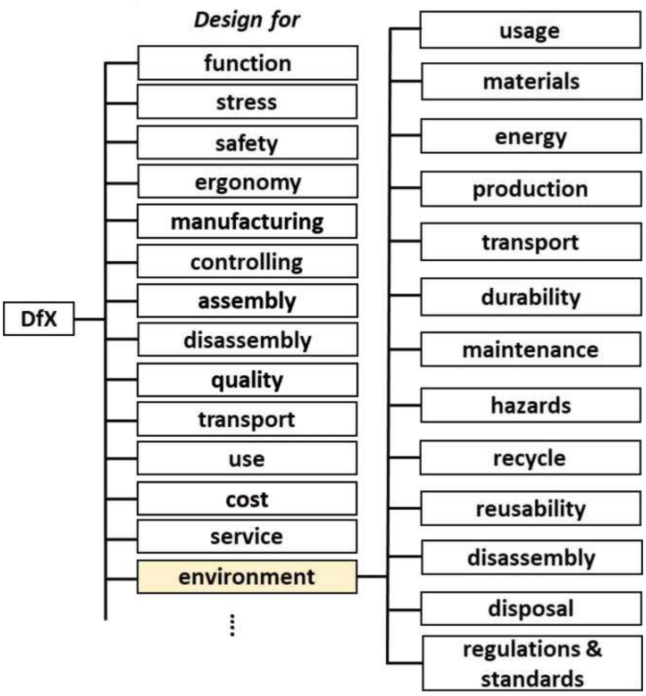

Figure 32, Hierarchical structuring of DfE

Moreover, total product weight can be also optimized by choosing right materials. Besides this, transport, distribution and packaging activities of raw materials, components and subassemblies are other evaluation aspects to decrease carbon footprint and create greener products. Therefore, effective processes for manufacturing, assembly as well as disassembly for the product parts have to be developed to provide recyclability and separability of final product. For example, minimizing joining elements, use easy to locate parts, modular design, geometric locking can improve assembly, disassembly, separability and consequently recyclability. Minimizing complexity and the amount of energy used in the manufacturing activities, moreover, optimizing required resource and energy during a product's use phase must be considered by using available guidelines, principles and experiences. Furthermore, elimination waste and toxic materials which have noticeable impact on the environment. Providing an effective maintenance, repair and upgrading through easy access and modular design which can accordingly extend the product life [Hauschild et al., 2004] [Telenko et al., 2008] [Kolur et al., 2020] [Fitzgerald et al., 2007].

5.6 Use Case – 3D Printer Development

A pilot factory (TU Wien Pilotfabrik Industrie 4.0) was set up at the Technical University of Vienna to research and to support for development of intelligent production systems. Innovative concepts and solutions are the main purpose of the pilot factory for a variety of serial production (low volume - high mix) in a variety of manufacturing enterprises. Integration of a realistic test environment with actual machines, real production chain and a real product in the pilot factory is needed for the development, testing, enhancement of new strategies and solutions for manufacturing industry. Therefore, 3D printer as a sample product in several variants was integrated in the pilot factory to study innovative manufacturing systems.

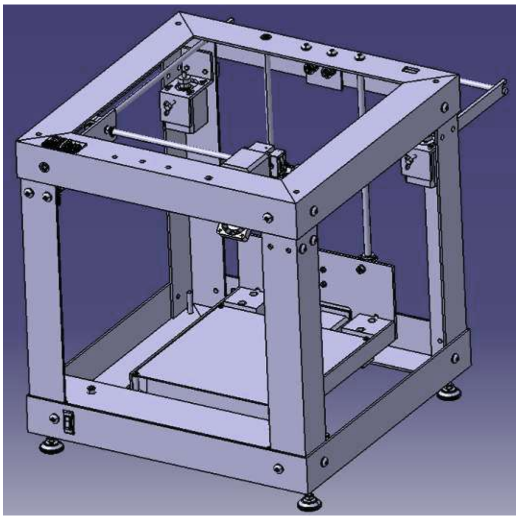

Figure 33, Demonstration of sample product 3D printer

3D printing technology has a significant innovation potential, in particular, regarding the hardware, materials and processes which are needed to create objects or parts in the additive manufacturing industry. This rapid technological changes in the process and material of 3D printing expands the amount of data and information to be considered in the evolution of 3D printing, therefore, the number of DfX-aspects and rules that must be considered become an indispensable factor. For this reason, a 3D printer is chosen as a use case for the aimed concept that is built on a KM and communication platform. The correct information at the correct moment must be provided for developers to minimize time and cost during any development process, that is what this concept has set a main goal.

One variant of the 3D printer in the pilot factory is presented in Figure 33. The shown 3D printer prints solid objects layer by layer using the FDM (Fused Deposition Modeling) technique, which relies on heating, melting and extruding thermoplastic filament through an extrusion head. The illustrated 3D Printer has following main components which are the X, Y, and Z Axis motors, the belt mechanism, the extruder, the drive shaft, the heater, the cooler, the filament spool holder, the print head and the guide block. The 3D printer's used components must be regularly improved and modified to meet new standards and needs. In the pilot factory, manufacturing processes like chipping and cutting, as well as machining centers for milling and lathing, are available for the production of 3D printer components. Manufacturing processes of these components have an impact on the 3D printer’s output design.

6 Prototypical Implementation of the Communication Platform

6.1 Software Requirements

To give an overview about the software requirements, in Figure 34 main software requirements of the DfX-based KM and communication platform are presented. In addition to main software requirements, section 6.2 explains in more detail application of each activity or function that is necessary for the realization of software prototype.

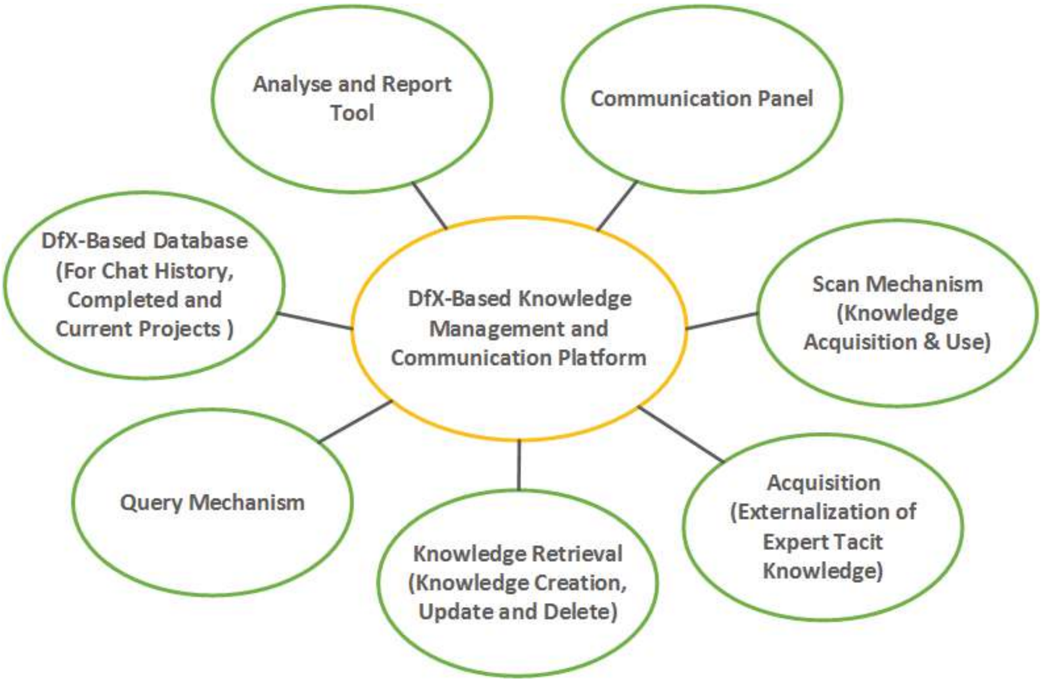

Figure 34, Functional requirements

Seven key requirements are used to summarize the requirements for the aimed communication software. The communication panel provides basically an interface for stakeholders to exchange information and ideas during conversation, moreover, to display messages and answers of users in the system. To provide a valuable and an effective knowledge acquisition and use in this concept a scan mechanism is defined as an essential need that is supported with natural language processing. Furthermore, a query mechanism has to be implemented to utilize, update and delete knowledge that is already saved in the DfX based storage. Acquisition of knowledge, in particular, externalization of expert tacit knowledge is the main purpose of this concept. Acquisition of this undocumented knowledge is supported by a tagging mechanism assisted by NLP since defining keywords performs a significant part in the presented KM and communication system for organizing and storage of knowledge. A DfX based storage has to be implemented to save chat history, and also knowledge about completed and current product development projects, moreover, user information. This function has to provide an effective storage of the identified knowledge through the connection of the defined keywords to the right DfX category for the structuring of knowledge that can be used by stakeholders or development teams in the product development processes. The software must also supply knowledge retrieval function for the creation, update and delete of knowledge which is possible without involving communication. By using analyze and report tool, frequently used key words can be detected from the system and presented to the stakeholders.

6.2 Software Functions and Activities

The primary functions of the suggested concept, which are illustrated in Table 4, must be executed to create the prototypical implementation of the communication platform. For a prototypical implementation thirteen activities are defined to achieve an effective knowledge generation, storage, sharing and use in the proposed communication platform. Eleven functions of the system are interactive activities performed through interaction between user and system during real-time communication of team members. For the identifying keywords to acquire and use knowledge, the scanning function as a background activity provides a tagging mechanism or keywords extraction supported with NLP. All these valuable interactions and activities are required to establish a unified knowledge management system to aid product creation processes in a company to assist employees with the critical and essential information during the decision-making processes.

Table 4, Software Activities

Activity No	Description	Type of the activity
A1	Login	interactive activity
A2	Communication	interactive activity
A3	Knowledge Retrieval	interactive activity
A4	Scanning for Identifying Keywords	background activity
A5	Storage	interactive activity
A6	Acquisition	interactive activity
A7	Create New Knowledge	interactive activity
A8	Update Knowledge	interactive activity
A9	Query	interactive activity
A10	Scanning for Knowledge Use	background activity
A11	Upload Data	interactive activity
A12	Delete Knowledge	interactive activity
A13	Create Knowledge Room	interactive activity

For a better understanding of the defined functions regarding this concept a use case with activities is presented in Figure 35 to clarify interaction between user and system. User can access to the system with a login function. After accessing in the system, query, communication and knowledge retrieval functionalities are available for the users. Moreover, users are able to create a new knowledge room or able to attend in already existing knowledge room to communicate with other team members. Communication includes acquisition activity that is supported with scanning function. Furthermore, query function is assisted also with scanning activity for knowledge use. Scanning for both knowledge acquisition and use is a background activity provided by the system.

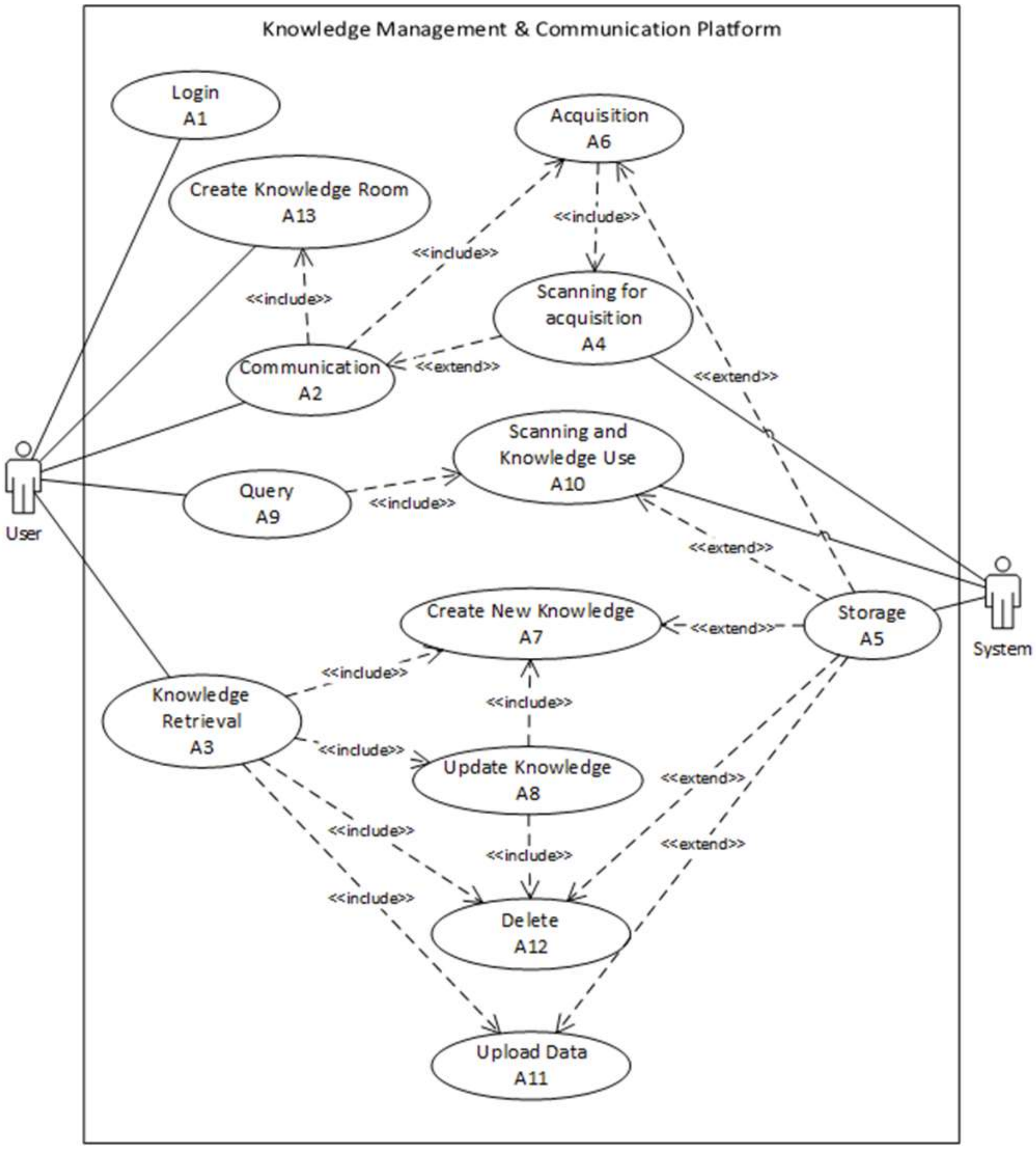

Figure 35, Use case and activities

Acquisition and use of knowledge must be connected with the storage to perform information transfer between user and system. Knowledge retrieval contains basically creation, update and deletion of knowledge. Create, update and delete activities are interactive activities and connected with the storage since the main focus is on the existing knowledge. All these activities have to provide an effective communication and knowledge management tool during a real-time messaging process so that employees can be supported with knowledge that is needed by any departments in the company.

6.2.1 Login (interactive activity)

User can enter in the system with username and password via a single point of access. If users don't have any account, they have to register and create an account, therefore, a secure communication platform can be generated where privacy and knowledge sharing are of crucial importance.

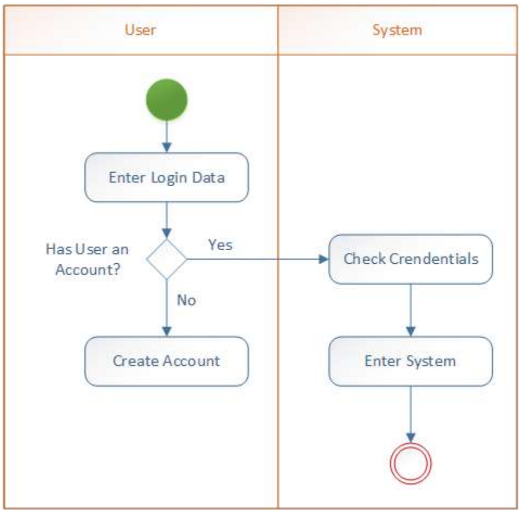

Figure 36, Login in the system

The stakeholders have to be supported basically with a role-based entrance for both internal and external development teams where appropriate, therefore, needed information from all department and from external stakeholders can be managed efficiently in a knowledge base. If the users enter into the system, there are two opportunities for the connection to the knowledge management tool by means of an integrated communication link or a search engine. These certain stakeholders, as a consequence, are able to exchange their knowledge in a digital communication platform where they need an access to apply it.

6.2.2 Communication (interactive activity)

After login in the system, users can access in communication page via creation of a knowledge room or choosing an existing knowledge room to attend in a real-time communication for the sharing of knowledge and information. The communication function includes also activities such as scanning for keywords, representation of knowledge for knowledge use, acquisition of knowledge, knowledge retrieval and storage of acquired knowledge with keywords linked to DfX aspects. The sharing of information and text messaging in a team collaboration during a meeting is also stored as a chat history in the system.

If the participants start messaging, the system scans the keywords during the communication, and users can see the detected keywords in the chat panel. At this point, a tagging process assisted by NLP is implemented to achieve knowledge acquisition, codes written in Appendix 1 and Appendix 2. For example, in the case of acquisition, information is requested from users, and they are able to enter the information into the system using the detected keywords. If the knowledge bearers want to implement their implicit or explicit knowledge in the system, the communication and knowledge management platform assists knowledge bearers saving the acquired knowledge by the Link of Keywords and DfX aspects to the repository. In this case, users have to select the correct DfX category and subcategory where appropriate based on the information.

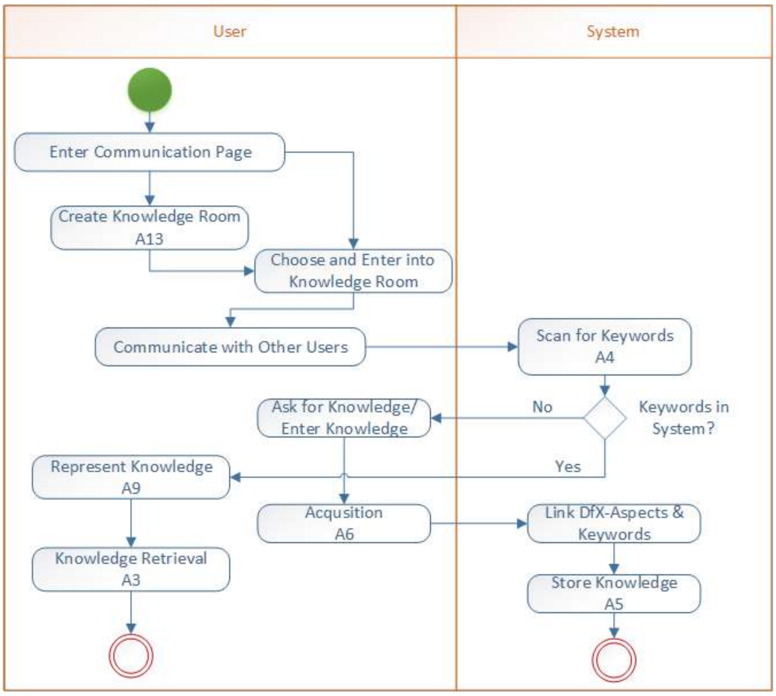

Figure 37, Communication in the system

On the other hand, identifying keywords during scanning is an activity that is applied for the user in communication platform to access and use the already stored DfX based knowledge. To do this, the system managing data must aid reusing of the information stored in connection with DfX. During communication and messaging activities between team members, the same tagging systematic is used for the detecting of keywords. Users get the information about the existing knowledge in the DfX based storage by the detecting keywords which they text and use during communication. In addition to the above-described knowledge representation or use, actually the knowledge usage stage works with the same mechanism as the knowledge retrieval that is possible with the integration of the query functionality. As a conclusion of these functions in an internal communications platform, relevant stakeholders are able to communicate and to share information effectively, therefore, they become main driver in the knowledge management tool to acquire and use development team's knowledge in a single place.

6.2.3 Knowledge Retrieval (interactive activity)

Knowledge retrieval function is provided through searching of keywords by using a query mechanism to support one of a knowledge management system's primary requirement for finding context based precious information within the DfX based data store. Basically, various ways are available for the information and knowledge retrieval with capable search function. However, a mechanism based on keywords search is implemented in our concept since specific keywords detected during communication by the system, moreover, users can select these keywords in a conscious. At this point, DfX based storage as a hierarchical knowledge structure brings a significant benefit together with keywords searching to impart appropriate knowledge to the appropriate person at the proper time. Users can access the knowledge and information that has been compiled across departments by using just one keyword search. Furthermore, users can also create or update knowledge through linking DfX aspects and keyword in the storage. After search result of the query, users can also apply a delete activity, however, this must be executed by a knowledge manager who has many years experiences and know-how in the company.

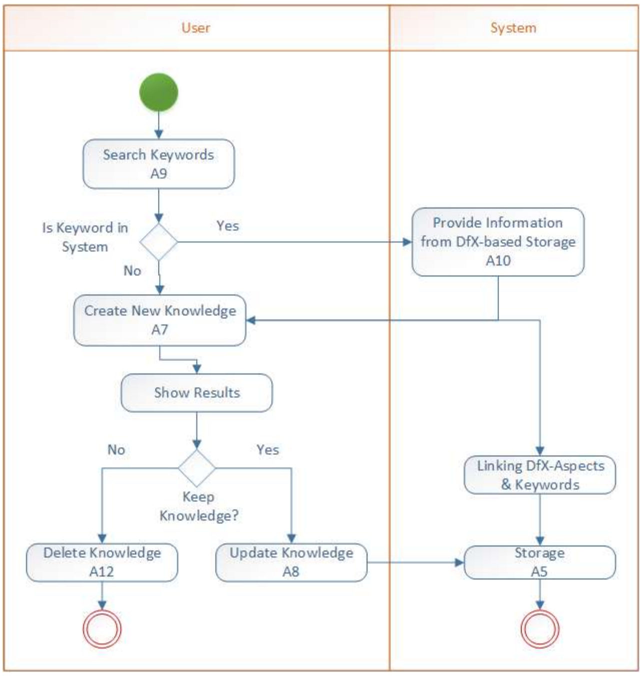

Figure 38, Knowledge retrieval in the system

The knowledge retrieval is an important function in a knowledge management system since acquisition of implicit knowledge basically depends on providing already existing knowledge to the stakeholders in an organization. For example, through knowledge retrieval explicit knowledge can be internalized by the users in the proposed communication platform so that users may receive assistance with generating new information or updating it with their thoughts and experiences. Therefore, implicit knowledge can be externalized and classified in the DfX based data base for a further knowledge reuse. As a result of the above explanation, knowledge retrieval function is necessary in this concept for both internalization and externalization processes as well as managing both tacit and explicit knowledge.

6.2.4 Scanning (background activity)

To perform a search for a disorganized information is mostly time and resource consuming process. Therefore, on the one hand, context specific expert's knowledge is acquired and stored with detected keywords in a structured form regarding DfX principles and aspects in this concept, on the other hand, a scanning process using keyword extraction is applied for use of knowledge. The Scanning by means of automatic keyword detection enables effective knowledge search, knowledge management and knowledge retrieval functions for the relevant DfX-based knowledge.

Keyword detection is implemented as a background activity in this concept during the communication of the users. When users enter text in communication panel or knowledge room, on the one hand system stores chat history, on the other hand, potential keywords are scanned and identified in order to support stakeholders for knowledge acquisition and knowledge use. For the knowledge use, system connects to DfX based database, in contrast to knowledge use, system utilizes chat history to define keywords for the knowledge acquisition.

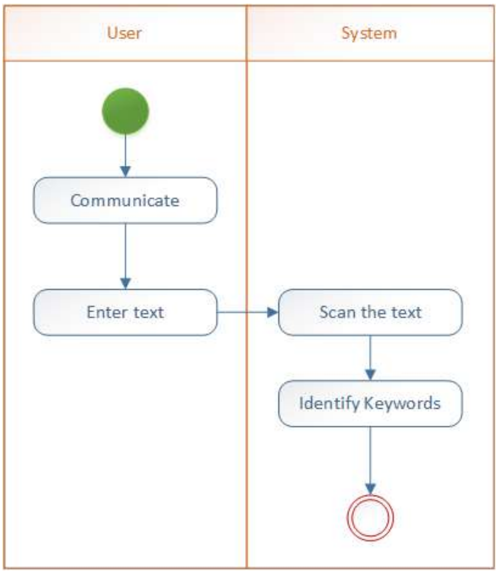

Figure 39, Scanning process for keyword extraction

Scanning of keyword begin with a given message or text by the users as shown in Figure 39, and then every word in the given text will be checked one by one. Firstly, the text is detected to find phrase delimiters and terms longer than two characters. Secondly, remain terms are analyzed to remove stop words for the identification of the most important content individual words or pairs of phrases. For the detection of stop words, a list of stop words has defined and implemented in the software. Thirdly, the content terms that have been detected to be left in the present text are compared to the content words that have been entered previously in the last ten messages in the chat history or knowledge room. According to this comparison most used content words that repeat the most within a text are automatically detected based on frequency approach, and main extracted keywords are defined and marked in the given text to recognize the main issues. The number of extracted keywords is limited to four due to the system performance and having a user-friendly system. Moreover, content words are also checked regarding to synonyms with a limit of five synonyms. The synonyms are detected by using an API (Application Programming Interface) based on https://www.datamuse.com/api/. All implemented functions for the extraction of keywords can be also realized manually, however, this process will be highly time-consuming.

6.2.5 Storage (interactive activity)

Storage is an interactive activity which takes place in three different ways. Firstly, users are able to give their knowledge in the system after keywords extraction in the knowledge room. System supports user to classify, and store acquired knowledge with related data or attachments in the DfX based structural knowledge repository. These keywords are automatically extracted by means of tagging mechanism (clarified in section 6.2.4). Secondly, users can share their knowledge in the system with the knowledge creation activity that can be performed without participating in communication, therefore, key words have to be defined by users manually, their codes depicted in Appendix 5. The last option is the knowledge update activity which has same functionality as in knowledge creation activity. However, in this case, keywords and acquired knowledge based on DfX category are already available in the storage, thus allowing only for update knowledge.

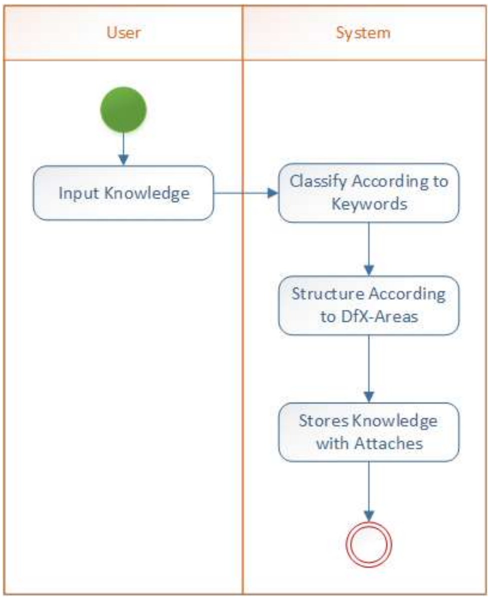

Figure 40, Knowledge storage

The core database consists of messaging history, knowledge from completed and current projects, and moreover, data about users and their roles. In this concept a MySQL database is created and installed on a cloud server that is provided by DigitalOcean that facilitates to access and reuse knowledge, moreover, also enhance the complexity to maintenance operations, updates and backup etc. Basically, there are two programs on the server, and both are in the same container. The first one is the MySQL server to run the database and the second one is Tomcat (web server) to execute the Java program.

6.2.6 Acquisition (interactive activity)

Knowledge acquisition is an interactive activity that provides one of the core process steps in proposed knowledge management and communication platform. This functionality allows users within organizations to acquire knowledge, particularly during real-time communication via text messaging. This feature is currently available in the cloud-based prototype. After users enter text messages in the knowledge room, the specified text is recognized, and potential keywords are identified. The system identifies frequently occurring keywords and notifies users of these terms.

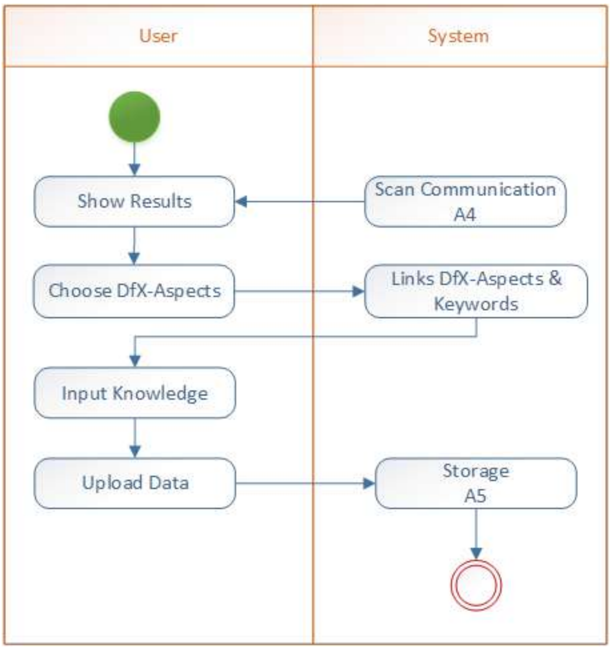

Figure 41, Knowledge acquisition

If users have implicit or explicit knowledge about the extracted keywords that they want to share in the communication system for the utilization in upcoming development projects, users can select the correct DfX category and subcategories and then specify the knowledge in the system. System connects already identified Keywords and chosen DfX categories automatically, and then users can submit their knowledge with related data or attachments in the storage, codes seen in Appendix 4. However, the attached file in the proposed prototype can be only pdf format, this will be obviously extended with other file types or formats.

6.2.7 Create New Knowledge (interactive activity)

Adding new knowledge to the system is planned as a feature that would allow users to add their knowledge without participating in communication. Users are able to put their implicit or explicit knowledge in the system with self-defined suitable keywords. In this case, keywords detection is not involved here in any way. Additionally, users must select the correct DfX aspects or categories to which their knowledge relates. Subsequent phases are completed as previously described sections in Acquisition (6.2.6) and Storage (6.2.5).

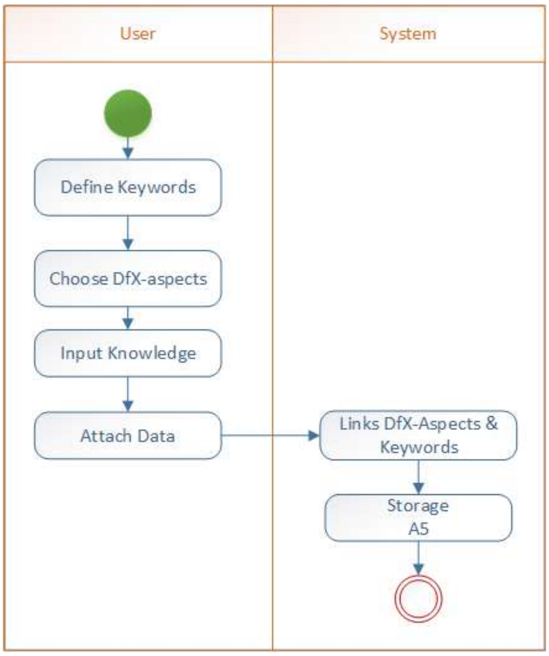

Figure 42, Create new knowledge

6.2.8 Update Knowledge (interactive activity)

In this activity, users have the opportunity to update existing knowledge. Just as new information can be added to existing knowledge, DfX category can also be changed and customized. Since knowledge development depends on the employees' implicit knowledge and experience of several fields, knowledge should be updated gradually and consistently. This means that knowledge can change dynamically depending on the person, situation and time. Moreover, knowledge of a product and development processes is also changing continuously due to customer's requirement, standards, new technologies, increasing complexity, etc.

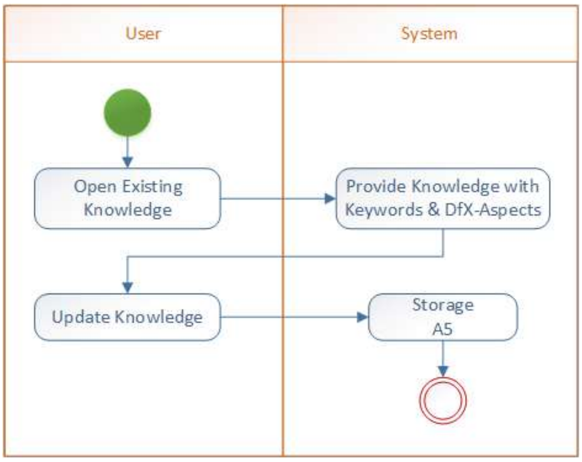

Figure 43, Update knowledge

6.2.9 Query (interactive activity)

Query is another function that can be applied without participating in communication. A user query in this interactive activity is basically a question by using potential keywords to search and represent existing DfX-based knowledge. For instance, during the early phases of product development, the project teams can apply queries to access the knowledge they require for their particular disciplines for the decision-making processes.

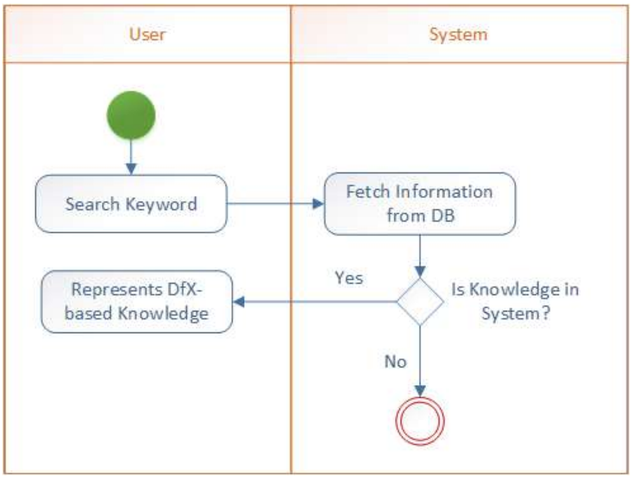

Figure 44, Query knowledge

6.2.10 Scanning for Knowledge Use (interactive activity)

Scanning for knowledge use is another core element of this concept. This activity is performed interactively between users and the system. The keyword extraction or tagging mechanism described in section 6.2.4, which is also used in the acquisition process, serves as the foundation for this functionality as well. As with the acquisition activity, the knowledge utilization feature also enables users in a development project to reach and utilize knowledge particularly during real-time communication, which currently occurs via text messages in the cloud-based prototype. The interactive knowledge use activity shown in Figure 45 begins with user communication. When users enter text messages in the knowledge room or chat panel, the system recognizes the specified texts to find keywords associated with DfX-based knowledge. As already explained, well-known and frequently recurring keywords are set in the system for the users and the users are made aware of them. After the keywords are found, users are informed about the knowledge regarding the DfX categories. Users can view the short description of the knowledge and associated DfX categories and subcategories, e.g., Design for the environment, and identify subcategories such as materials, transport, disassembly, etc. When users want to see knowledge, the system is able to submit, transfer and present available knowledge, their codes represented in Appendix 3. This function is available for each existing knowledge room or communication panel where various and independent development teams are working on projects.

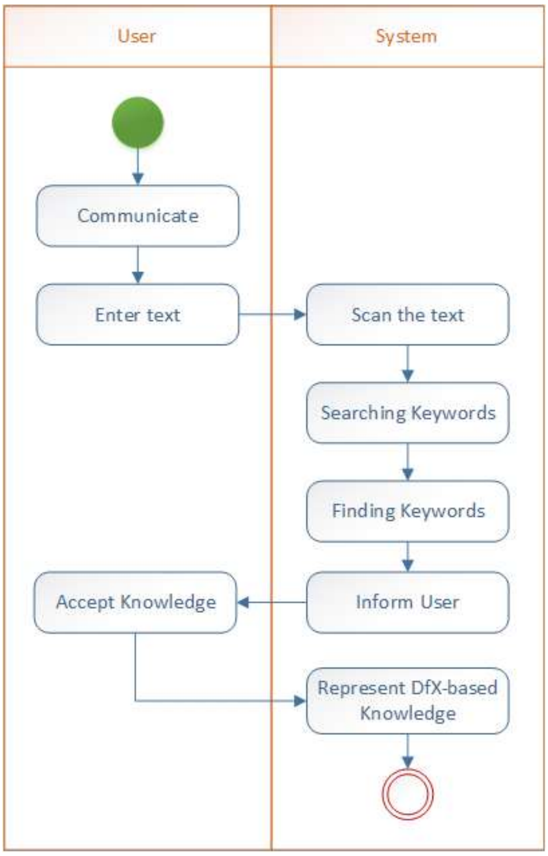

Figure 45, Scanning for knowledge use

6.2.11 Upload Data (interactive activity)

This function allows users to access existing knowledge and upload multimedia, content or documents which are related to DfX-based knowledge. Currently only documents with PDF format are accepted in the prototype and other file formats can be also added in the future.

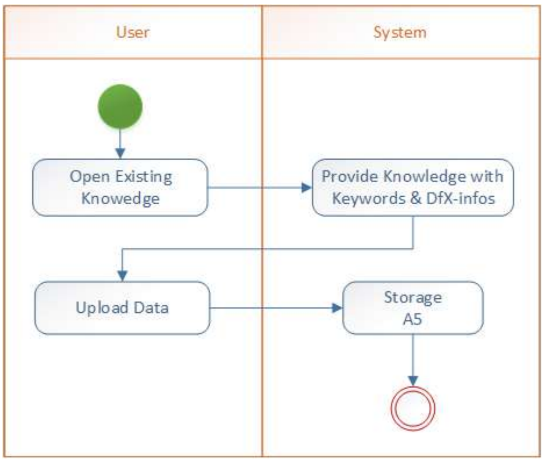

Figure 46, Upload data

6.2.12 Delete (interactive activity)

This activity allows users to delete already generated, structured and stored knowledge with its contents, data and attachments. In the proposed approach, acquiring knowledge, particularly tacit knowledge, takes time, therefore not every user can use the deletion function. In this situation, a role that must be specified is that of a knowledge manager, who is in the role of managing the knowledge gained. The knowledge manager has the option to delete existing knowledge. In the part on the prototype application that covers user rights and roles, this problem is addressed in more detail.

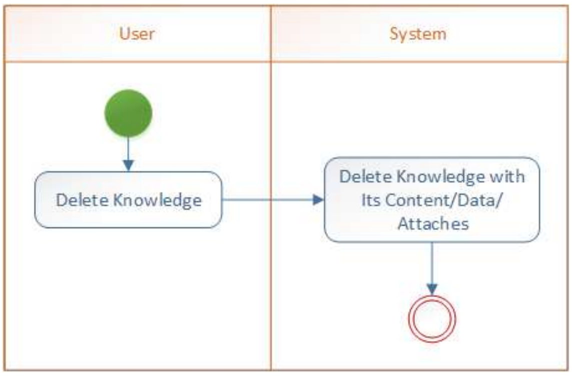

Figure 47, Delete knowledge

6.2.13 Create Knowledge Room (interactive activity)

In this concept, the knowledge room provides a communication platform or chat panel where users can participate in communication with their defined roles in the organizational structure. When users select the communication option after login in the knowledge management and communication platform, they can either participate in the existing knowledge rooms or create a new knowledge room with permitted roles.

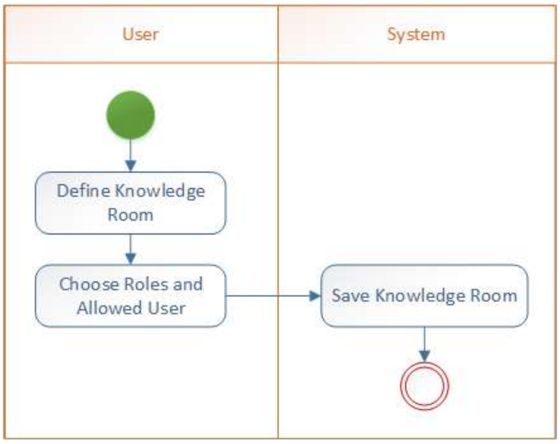

Figure 48, Create knowledge room

7 Application of the Prototype

An application example of the implemented rough prototype, based on a use case for 3D printer development, is demonstrated in this section. The intended concept is tested using core software requirements and functions of the communication platform. Main knowledge management process steps like acquiring, structuring, storage, dissemination and use are applied and highlighted.

Table 5 defines exemplary user roles and rights that should be used to apply the prototype. A comprehensive definition of the stakeholders who can access and use the system to guarantee a collaborative knowledge management environment was outlined in section 5.1. Internal stakeholders, including senior development engineer, development engineer, quality manager and production engineer, may potentially use the prototype for testing. The knowledge manager plays a crucial function in maintaining the knowledge that has been acquired and stored. Knowledge manager is the only user who is allowed to delete knowledge in the database. All users can perform functions such as creating knowledge and knowledge room, moreover, query and use knowledge. In addition, only certain stakeholders are authorized to update knowledge, e.g. knowledge managers and senior engineers.

Table 5, User roles and rights

Rights / Roles	**C** Creation knowledge & knowledge room	**W** Knowledge update	**R** Query and use knowledge	**D** Knowledge delete
KM: Knowledge Manager	+	+	+	+
SDE: Senior Development Engineer	+	+	+	
SPE: Senior Production Engineer	+	+	+	
PM: Project Manager	+		+	
QM: Quality Manager	+		+	
DE: Development Engineer	+		+	
PE: Production Engineer	+		+	
AE: Assembly Engineer	+		+	
TS: Technical Service	+		+	
CS: Customer Service	+		+	
...				

To evaluate and test the software functionality, two separate 3D printer development projects are created as application scenarios. Project A is utilized to create the first variant of the 3D printer, whereas Project B is employed to build the second variant of the 3D printer. Project A tests and demonstrates the acquisition, creation, structuring and storage of knowledge. The use of Project B makes it possible to use, retrieve and query knowledge that is generated during Project A.

7.1 Application of the Prototype for Project A

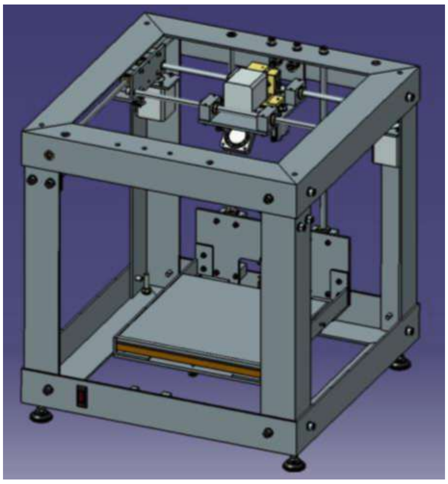

Figure 49, The first variant of the 3D printer

For the application of the preliminary prototype of the communication platform, the acquisition, creation, structuring and storage of the DfX-based knowledge are first applied in the application scenario of the 3D printer development Project A. Activities (see section 6.2) like login (A1), communication (A2), scanning for identifying keywords (A4), storage (A5), acquisition (A6), create new knowledge (A7), upload data (A11) and create knowledge room (A13) are tested with regard to the use case of developing the first variant of the 3D printer. In the application scenario Project A, the engineering team focuses mainly on problems relating to the drive shaft and extrusion. Knowledge generation and storage are performed by team members based on their area of expertise or DfX while working on engineering tasks to solve various technical design issues of 3D Printer.

7.1.1 Communication in the Knowledge Room Project A

Team members can create a knowledge room with a specific topic or project name in the communication platform after completing a role-based login into the system. Figure 50 presents the main page of the prototype with three options for connecting to the knowledge management system by means of a query, knowledge retrieval and integrated communication. The query function is used to find and access stored DfX-based knowledge by using identified keywords. By selecting the knowledge retrieval, user can create and update knowledge. The third is the communication, which includes an interactive communication environment based on various knowledge rooms, as well as a keyword and DfX-based component for knowledge use.

In Figure 51, a knowledge room with the name “Project A” is created to implement and test the planned application scenario for developing the first variant of the 3D printer. A quality manager, a development engineer, a project manager and a designer select the communication page and participate in Project A to collaborate and share knowledge about the current tasks in the development of the 3D printer first variant. During the development of the first variant, the engineering team focuses on issues and requirements relating to drive shaft and extrusion. Accordingly, communication in the knowledge room Project A progresses depending on drive shaft and extrusion.

Figure 50, Main page of the software prototype

During communication in the knowledge room Project A, participants have access to activities such as keywords extraction, representation of knowledge based on keywords and DfX categories, acquiring knowledge, structuring and storage of acquired knowledge by means of identified keywords and associated DfX aspects.

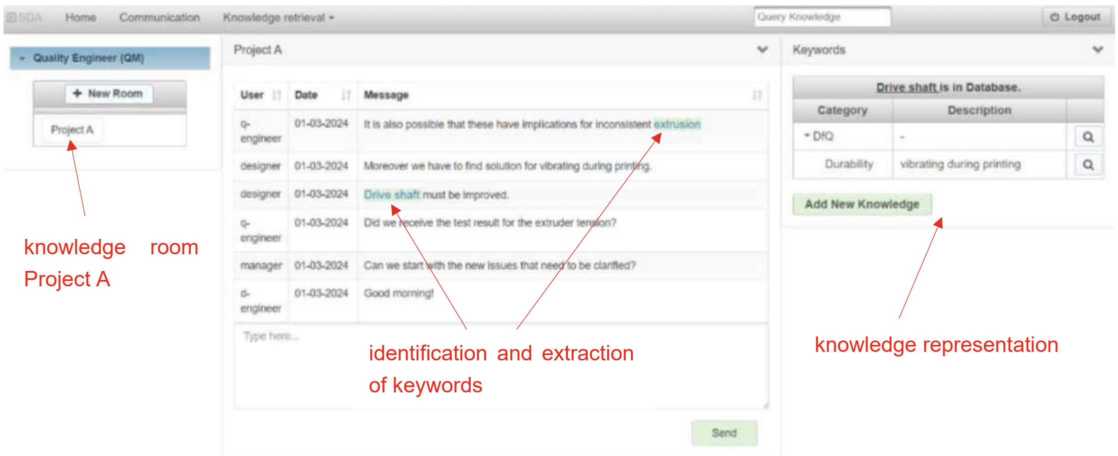

Figure 51, Identification of keywords for knowledge acquiring and representation during communication in the knowledge room Project A

The system detects keywords during messaging and communication activities, and development team of Project A can view the identified keywords on the chat panel. In this phase, an NLP-supported tagging mechanism is implemented to support users in acquisition and use of knowledge. By linking the extracted keywords, DfX category and subcategory with the repository, knowledge bearers can, for example, contribute the necessary implicit or explicit knowledge to the communication and knowledge management platform when acquiring knowledge. For the knowledge use, users receive the information about the existing knowledge in the DfX-based storage by activating the extracted and marked keywords, which they text and message during communication in the knowledge room.

7.1.2 Knowledge Acquisition and Storage

Acquisition (A6) as a core process step includes keyword extraction (A4) as a background activity, determination of DfX categories and creation of knowledge (A7). Acquisition as an interactive activity allows users to generate knowledge in organizations during real-time communication. Acquisition starts with a text input during communication in the knowledge room Project A. The designated text in the knowledge room is detected and the most frequently used keywords are identified. The user is made aware of the most frequently occurring keywords and has the option to set these recognized keywords in the system.

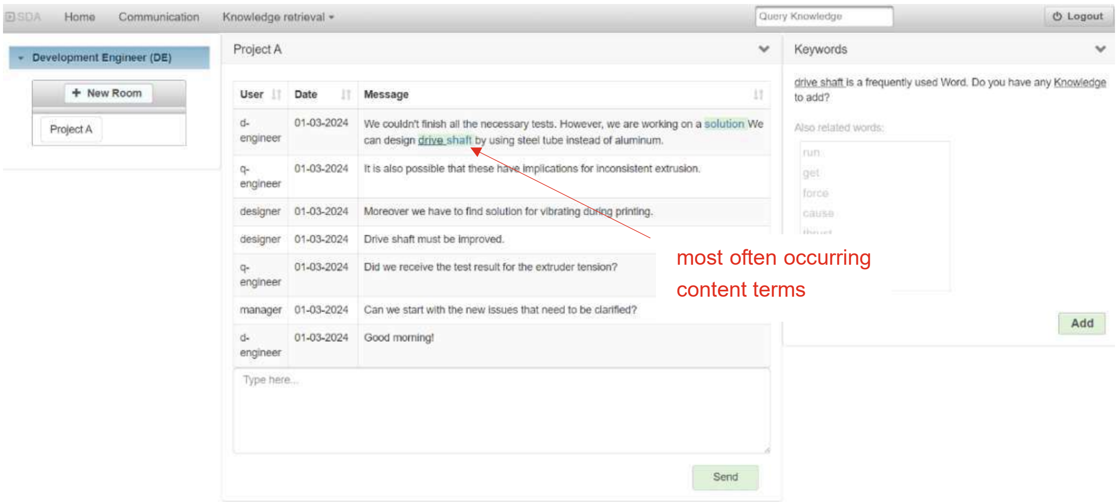

Figure 52, Keyword extraction for knowledge acquisition

In Figure 52, a keyword extraction example is presented. The project team holds a conversation about improving the reliability and durability of 3D printing (DfQ) in the knowledge room Project A. Team members concentrate on developing the drive shaft using steel tubing instead of aluminum while communicating in real time. After a text "We couldn't finish all the necessary tests. *However, we are working on a solution. We can design drive shaft by using steel tube instead of aluminum.*" is entered by the development engineer, system starts keyword extraction via the chat history. Each word of the given text is checked individually. First, the entered text is searched for terms that are longer than two letters and for phrase delimiters. Secondly, the remaining words are analyzed to eliminate stop words in order to determine whether content single or pairs of words are most crucial.

Delimiters: [., ,, ., .]

Stop words: [*we*, *couldn't*, *all*, *the*, *however*, *are*, *on*, *a*, *can*, *by*, *instead*, *of*]

Content words: [*finish*, *necessary*, *tests*, *working*, *solution*, *design*, *drive*, *shaft*, *using*, *steel*, *tube*, *aluminum*]

Thirdly, the content terms left in the present text are contrasted with those that were previously entered into the knowledge room Project A. This comparison shows that the most frequently occurring content terms in a text are automatically found using a frequency technique, and the primary extracted keywords are identified and highlighted in the original text to help identify the most relevant and key issues.

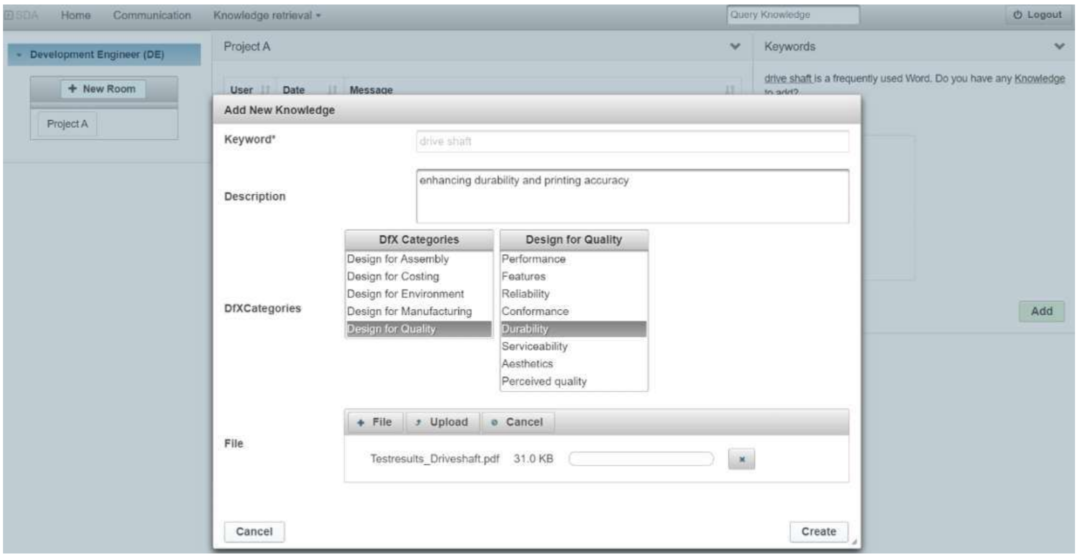

Figure 53, Creation of knowledge by using extracted keywords and determined DfX categories

Finally, the development engineer acquires knowledge by using the extracted keywords "drive shaft", as shown in Figure 53. If the development engineer has implicit or explicit knowledge about the drive shaft, he or she can release this knowledge in the communication system for the use in future development projects.

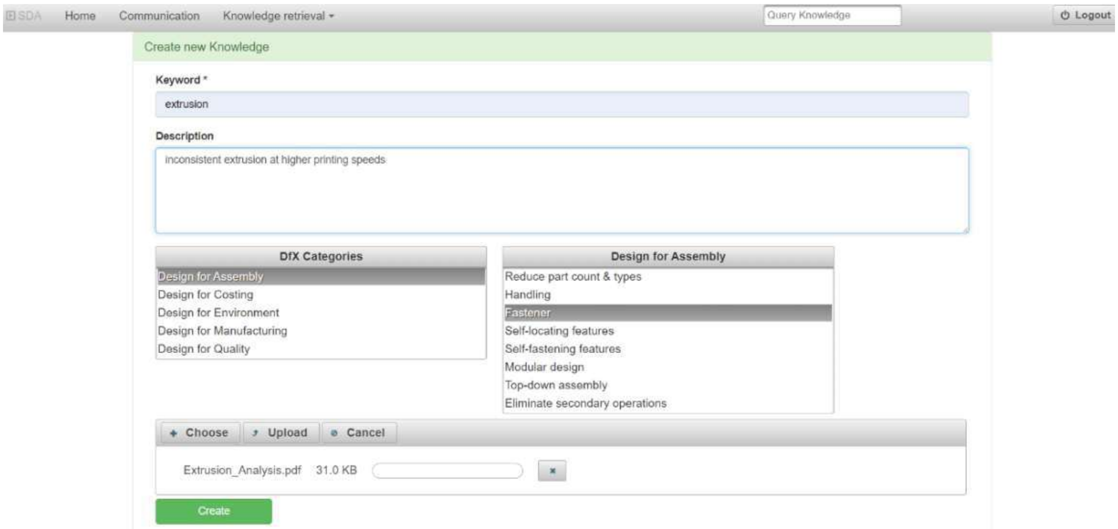

Figure 54, Creation of knowledge by using knowledge retrieval option

The development engineer is able to select the appropriate DfX category "DfQ" and the subcategory "Durability", furthermore specify a description of the knowledge in the storage. The software automatically connects the already extracted keywords "drive shaft", the chosen DfX categories "DfQ" and "Durability", moreover, the knowledge with related data or attachments can be submitted in the DfX-based structural knowledge storage. However, the attached file in the proposed prototype can only be pdf format, this may be obviously extended with other file types or formats.

It is also possible to create knowledge without taking part in communication. For a direct knowledge creation activity users select the knowledge retrieval option (Option 2 in Figure 50) and activate the create knowledge function. After choosing “Create new knowledge page”, users are able to provide their knowledge. As shown in Figure 54, the quality manager has manually entered a self-defined suitable keyword “Extrusion” and placed his or her knowledge in the system. Additionally, the quality manager has selected the related DfX categories “DfA” and “Handling” for structuring the knowledge in the DfX-based repository.

7.2 Application of the Prototype for Project B

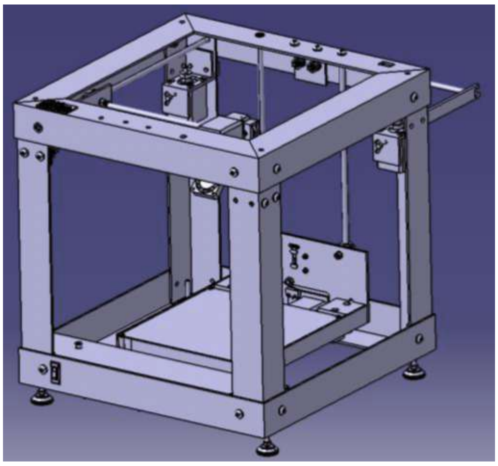

Figure 55, The second variant of the 3D printer

This section considers the development of the second variant of the 3D printer for the application scenario Project B. During Project B, activities such as login (A1), communication (A2), knowledge retrieval (A3), update knowledge (A8), query (A9), scanning for knowledge use (A10), delete knowledge (A12) and create knowledge room (A13) are carried out and examined. The generated, structured and stored DfX-based knowledge with the keywords drive shaft and extrusion in the application example of Project A are main focus points for the application of the preliminary prototype of the communication platform.

7.2.1 Communication in the Knowledge Room Project B

After a role-based login of the team members to the system, a new knowledge room with the name "Project B" is generated to connect the knowledge management system and enable knowledge-based communication on engineering topics. Figure 56 shows an interactive communication environment for Project B, which also contains a keyword- and DfX-based component to test the planned application scenario for the query, retrieval and use of knowledge.

To collaborate and exchange information regarding the current tasks during development of the second variant of the 3D printer, a quality manager, a senior development engineer, a development engineer and a senior production engineer choose the communication page and participate in Project B. Participants in the knowledge room Project B can engage in activities like keyword extraction, knowledge representation based on keywords and DfX categories while communicating.

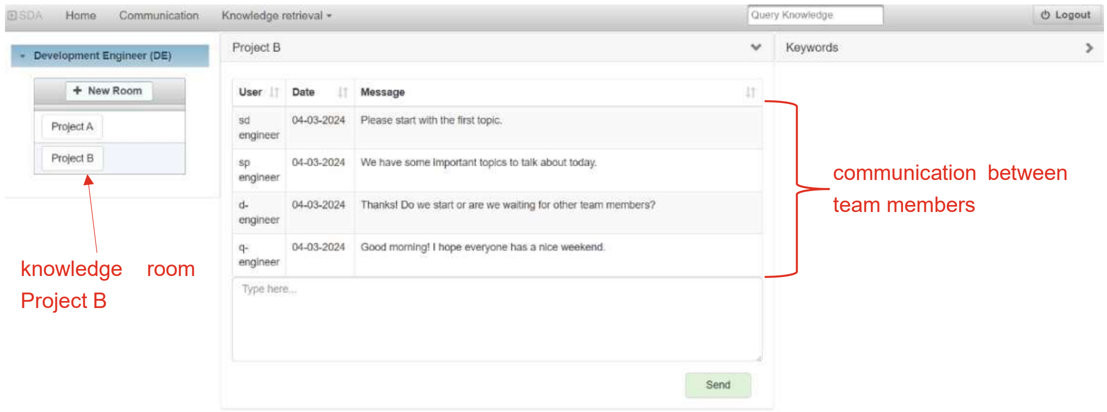

Figure 56, Communication in the knowledge room Project B

7.2.2 Knowledge Use

Use of knowledge can be provided in the proposed concept through keywords extraction during real-time communication or using a query. Keyword extraction allows users on the communication platforms to retrieve and use previously stored DfX-based knowledge.

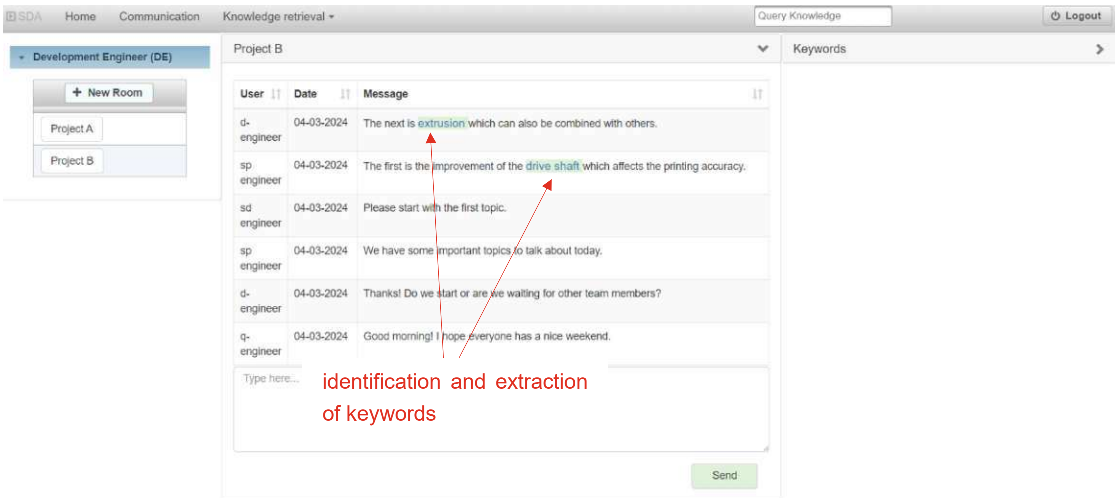

Figure 57, Keywords extraction during communication in the knowledge room Project B

The Figure 57 presents the messaging activities between team members in the knowledge room Project B. During messaging and communication, the knowledge management system identifies keywords and participants can view the identified keywords “extrusion” and “drive shaft” on the communication panel. The keywords “extrusion” and “drive shaft” were applied for the acquisition and storage of knowledge with the determined DfX categories in the DfX-based storage while Project A. The connection of the generated necessary implicit or explicit knowledge to the communication and knowledge management platform with the extracted keyword and appreciated DfX categories is the main goal of the preliminary prototype.

For the use of knowledge by means of keywords extraction, senior production engineer activates the marked keyword “drive shaft” as shown in Figure 58. In the DfX-based storage area in the knowledge room, the information about the existing knowledge is presented with a brief description and DfX categories. The keyword “drive shaft” and necessary information were given while the engineering team of Project A focused on issues and requirements relating to the drive shaft for the development of 3D printer first variant.

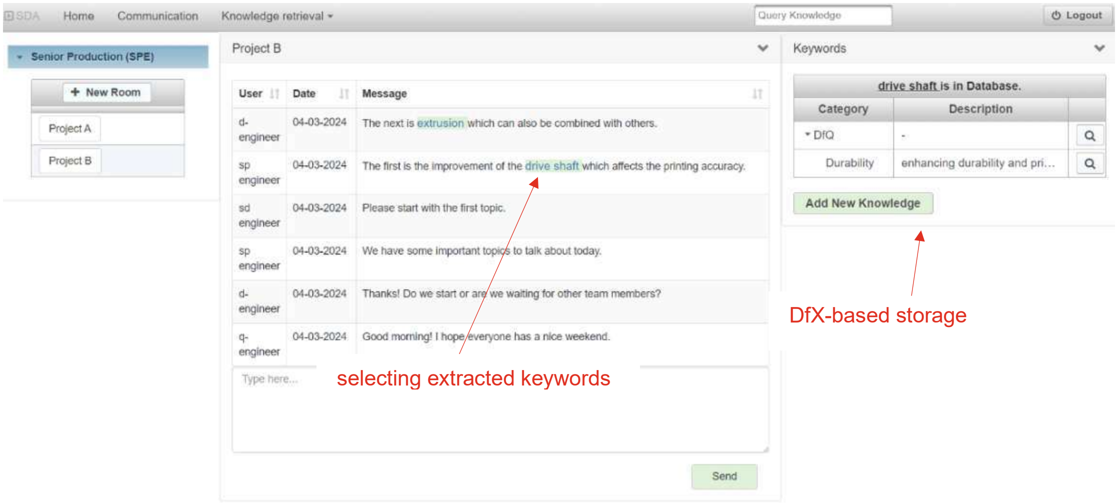

Figure 58, Access DfX-based knowledge by activating extracted keywords

If the senior production engineer wants to retrieve detail information about the drive shaft, the product designer can select and activate the corresponding subcategory link in the DfX-based storage area. In Figure 59 existing knowledge is presented with the information about the date of creation, user to whom the knowledge belongs and submitted related data or attachments. The user can also view the entire description of the created knowledge in detail.

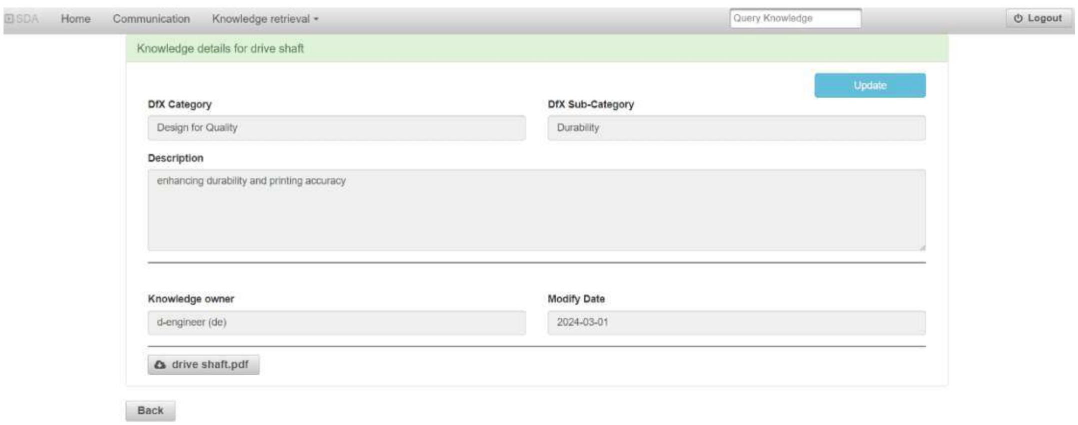

Figure 59, Use of Knowledge

For the use of knowledge by a query users enter letters or keyword in the search option to find available DfX-based knowledge in the repository. In Figure 60 development engineer applies a query to search knowledge about belt tension without participating in communication and system shows the results related DfX aspects. The same process as using knowledge during communication, the development engineer selects and activates the corresponding subcategory to retrieve detail information about the drive shaft or extrusion.

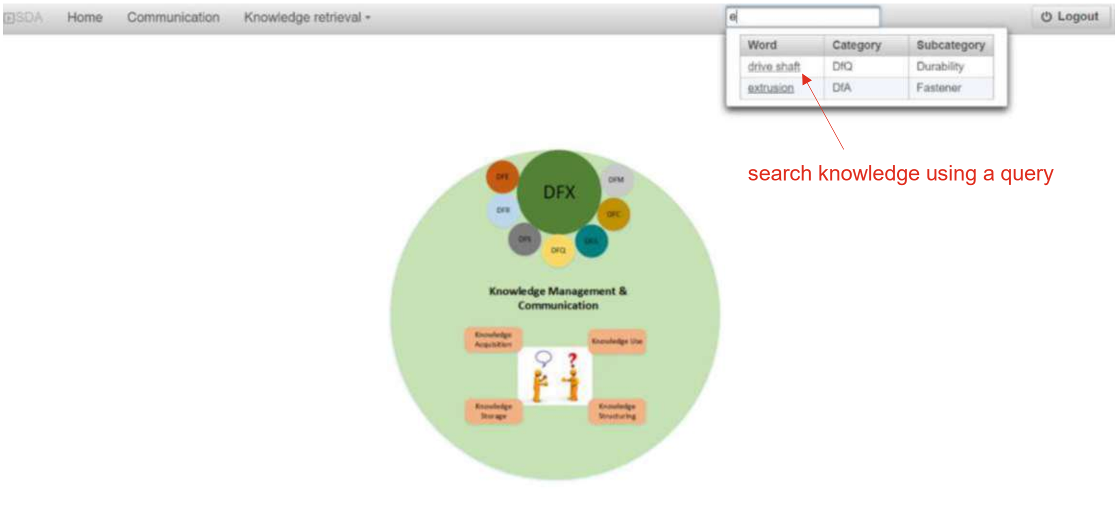

Figure 60, Query

7.2.3 Knowledge Retrieval

In addition to the above-described knowledge use, knowledge update or delete can be conducted using knowledge retrieval function. The integration of query functionality into the knowledge retrieval process follows the same methodology. However, knowledge update can be performed by certain roles, such as seniors, and knowledge delete is only possible for knowledge manager. Furthermore, knowledge manager can delete users and knowledge rooms in the communication platform.

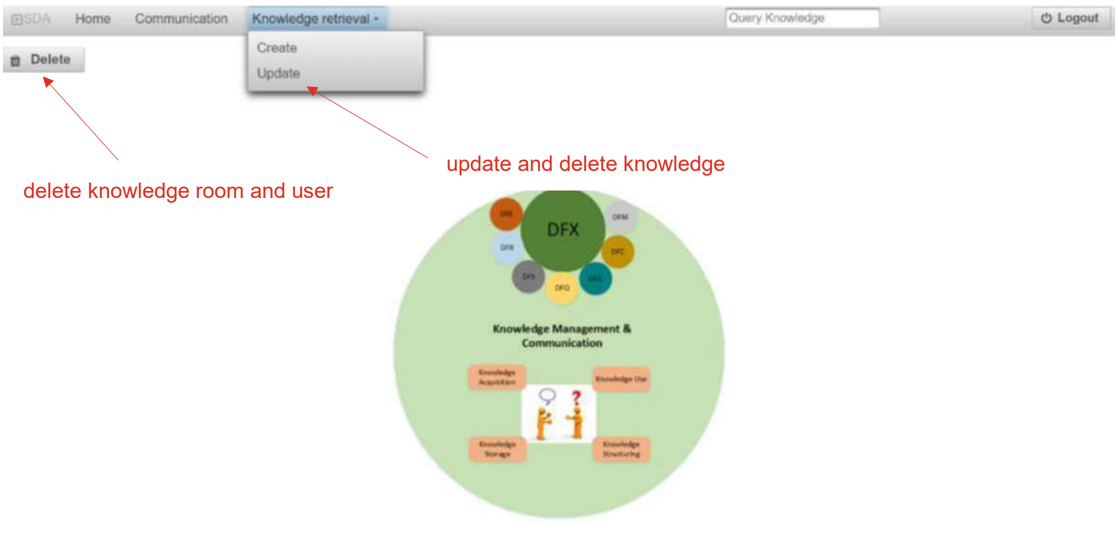

Figure 61, Knowledge retrieval, delete of user and knowledge room

To update or delete knowledge, as shown in Figure 61 knowledge manager is able to apply knowledge retrieval option in the communication platform at first. After selecting knowledge update, knowledge manager can use the query function with the keyword “drive shaft” and find out a list of existing knowledge (see in Figure 62). Knowledge manager can specify the list of result according to DfX categories for the representation of proper knowledge.

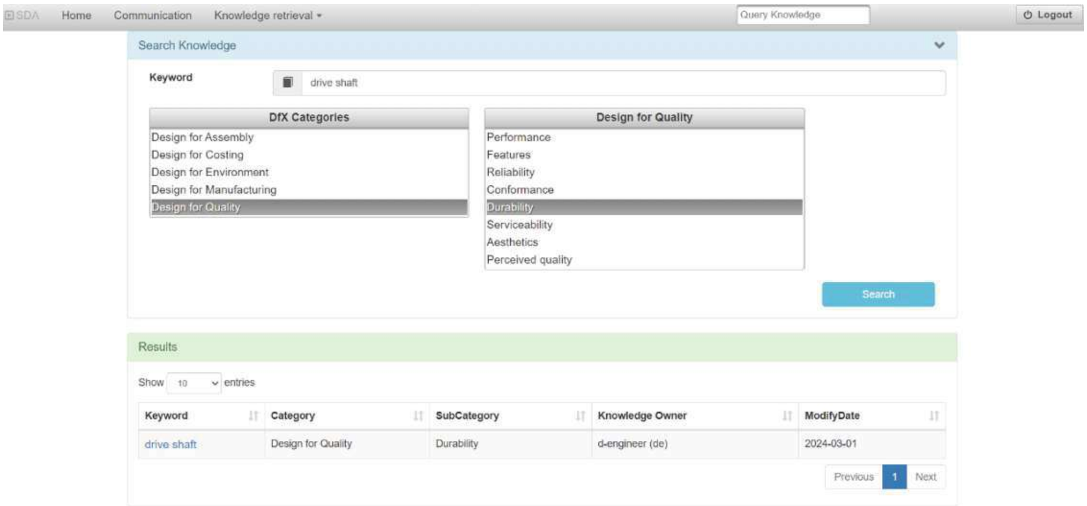

Figure 62, Searching of knowledge

As shown in Figure 63 knowledge manager can update with some new information and also upload some data after activating the keyword "drive shaft". If the knowledge is not true or includes fundamental mistakes, knowledge manager can delete existing knowledge and data.

The communication scenario between Projects A and B illustrates how knowledge is gathered, organized, saved, and presented using keywords connected to DfX categories, providing a conclusion to the functions of a communication platform that have been previously described. The key elements of knowledge management that allow users to gather knowledge instantly throughout product creation, are realized through the collaboration of both individuals and systems.

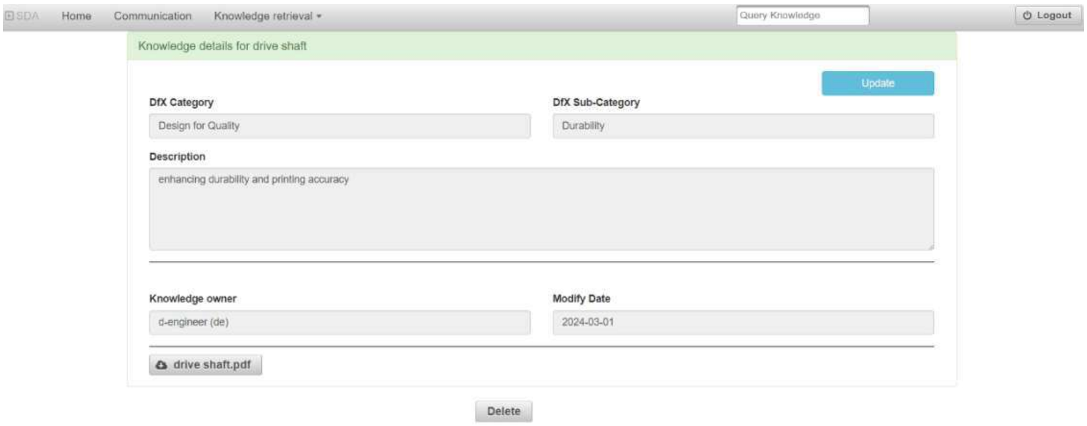

Figure 63, Knowledge update and delete

8 Conclusion and Future Works

To survive in global competition, companies require varying teams to create novel ideas, particularly in product development that represents a highly intricate subject matter area. Using collaboration technologies to facilitate effective communication and teamwork is essential for successful product development in an information and knowledge intensive landscape. In order to avoid costly errors and knowledge loss, comprehensive communication supported with knowledge management systems is crucial for decision-making processes. The appropriate technologies are critical for a successful collaboration in product development, regardless of whether engineering teams work closely to enable casual meetings or collaborate virtually to be flexible.

In the course of this doctoral thesis, a DfX-based knowledge management and communication platform was developed for the improvement and promptness of the decision-making processes particularly in the initial phases of developing a product. Experts' implicit and explicit knowledge from various fields can be efficiently captured, stored, disseminated, and used with the help of created communication platforms. The focus on management of knowledge from different areas regarding to numerous DfX aspects such as manufacturing, quality, assembly, ergonomics and environments in the communication tool to provide an effective knowledge transparency and knowledge sharing within the company, which has so far been insufficiently considered. For fulfilling this crucial requirement, the suggested solution has the capability to have significant impact on the way companies handle and use knowledge in the age of digital technology. Additionally, implicit knowledge of experts can be acquired in an organized manner and shared at the team-level using keyword detection, providing the necessary knowledge at the appropriate time while decision-making. Furthermore, the generated tool prevents loss of expert knowledge through targeted implementation of communication, so that sustainability in the product development is positively influenced trough the integration and access of the most up-to-date design intent knowledge regarding DfX aspects.

In order to assist transfer to a new subject area, this research first examined a number of methods, technologies and tools based on DfX, knowledge management and communication separately from the perspective of product development. Taking the identified resources into account, a holistic approach was created for a goal-oriented and systematic linking of knowledge management and communication based on DfX aspects in the scope of product development. Based on this, a detailed concept (see section 5) was determined for the implementation of a software solution. During implementation, a prototype (see section 6) was developed that enables the use of a DfX-based knowledge management in a communication platform. The application of the prototype (see section 7) was realized using a case study through a communication scenario for the development of a 3D Printer between Projects A and B.

The purpose of this thesis is to provide answers the following research questions which play a central part in the analysis and identification of a process-model for finding out an effective concept and solution addressed key points.

How should a process-model be built to assist development team in the initial phases of product development for decision-making processes?

The main resource of decision-making and idea generation process during product development is the development team member involved. Since the best feasible decisions based on knowledge, an organized and methodical management of knowledge has to be provided in the company on the one hand, but also fostering team members to provide their knowledge and expertise on the other hand. In particular, active sharing of knowledge in real-time must be examined more closely. To support concurrent processing of knowledge-intensive tasks, a holistic approach must be found to deal with this problem. The main goal therefore must be to integrate a knowledge management approach for knowledge creation, storage, sharing and application into an appropriate synchronous communication system. The application of this approach model can improve the gathering of experts' implicit and explicit knowledge during cooperation and transferring acquired knowledge to the interdisciplinary development team level.

How systematically the experts' tacit knowledge and experiences can be goal oriented acquired from various areas in the product development process and transferred into an explicit form?

Before knowledge carriers, especially experts, leave the organization, a sustainable generation and integration of their non-negligible knowledge and experiences must be provided. The acquisition and storage of tacit knowledge from different areas during the application of a development project in a structured manner promotes the updating and improvement of existing knowledge within the organization. In this context, using DfX methodologies and approaches as a knowledge system and codification strategy is a major benefit for a purpose-driven connecting and gathering of knowledge from several fields, therefore, multidisciplinary development teams can reach context-based information. Therefore, systematically capturing and storing explicit and implicit knowledge across DfX categories and subcategories is one of the essential goals of the methodological approach given. By combining the hierarchical structure of the DfX aspects and developing them into various degrees of detail, a context-based knowledge management system may be accomplished. In the first stage, five DfX categories with identified subcategories are employed to develop the prototype. The categories that have been integrated are Design for Assembly (DfA), Design for Costing (DfC), Design for the Environment (DfE) Design for Quality (DfQ) and Design for Manufacturability (DfM).

Which methods should have this process-model therefore the acquired domain-specific knowledge can be made available or visualized to the developer at the appropriate time and quantity?

Not only the creation, structuring and storage of domain-specific knowledge but also the fulfilment of the rapidly dissemination and representation of knowledge must be provided in the knowledge management and communication tool while the development team collaborates. To speed up the use of knowledge in a systematic manner, a keyword extraction and tagging process based on natural language processing (NLP) is implemented in the communication tool. The keywords extraction for a collaborative tagging enables users to access more quickly classified digital content so that the knowledge gained from finished projects may be successfully shared and used in the communication platform. The feasibility of the detection of key terms from textual data during communication is demonstrated by the prototype implementation and application.

Which aspects and requirements must include the process-model, on the one hand, in order to improve knowledge transparency and effective knowledge sharing across distributed design teams, on the other hand, to provide effective use of acquired knowledge?

To improve knowledge transparency and effective knowledge sharing across distributed design teams, the process model should include the fundamental KM processes including acquisition, structuring, preserving, transfer and use of knowledge. It should also incorporate mechanisms for real-time communication and tools for capturing and organizing knowledge. Additionally, the model should provide an effective system to gather lessons learned from team members. For the realization of these aspects and requirements, the developed prototype has three fundamental parts that are knowledge management, communication and DfX-based storage. The communication part aims to assist team members with an effective knowledge acquisition, retrieval and representation by means of keywords extraction and tagging mechanism assisted by NLP. Knowledge management component ensure basically organizing and storage of created knowledge in a structural form by means of key words and linking this undocumented knowledge in the area of DfX. In addition, a DfX-based storage is implemented to save chat history and knowledge about completed and current product development projects. Furthermore, a query mechanism is implemented to utilize, update and delete knowledge that is already saved in the DfX based storage. Overall, a well-designed process model is implemented to facilitate the use and sharing knowledge within distributed design teams.

Considering the results of this work, there is a need for new or extended research to further develop fundamental knowledge management processes such as gathering, storing, disseminating and using knowledge for the fulfilment of the requirements arising from product development. In addition, the resulting solution also focuses on improvement of communication technologies, so new perspectives in terms of performance and knowledge sharing must be considered for the use of such a system. Possible future research areas include, for example, refining the communication platform by improving the machine learning (ML) and integrating artificial intelligence (AI) techniques for versatility and usability. AI can manage and use acquired information and define required knowledge in a number of formats, enabling developers to be more efficient and proactive in supporting rapid knowledge transfer and identifying errors in earlier product creation. Moreover, the connection of the presented communication platform to other existing systems, in particular knowledge-based engineering, PLM and CAD, may lead to a comprehensive linking and use of all valuable information and knowledge. Furthermore, the prototype presented in this study was tested using a case study to demonstrate its basic operability. However, testing in a real industrial setting could provide more information about the potential and weaknesses of the system, particularly with regard to enhance the platform's effectiveness. It is of great importance to place emphasis on the connection of best practices and lessons learned in a DfX knowledge base for cross-company applications and resulting data security of crucial design knowledge.

Figures

Tables

Appendix

Appendix 1 Process Message in Communication (A2)

```
public void processMessage() {
        try {
            KnowledgeRoomMessageView messageView = new
KnowledgeRoomMessageView(SDAUtil.generateUuid(), enteredMessage, new Date(),
currUser, activeRoom.getUuid());

            for (MessageView word : messageView.getWords()) {
                if (checkWordUseful(word.getWord())) {

word.setSynonyms(apiService.findSynonymsWithDataMuse(SDAUtil.trimStringFormCharac
ters(word.getWord())).getSynonyms());
                }
            }
            messageView.copyView(processGivenMessage(messageView));

            activeRoom.getHistory().add(0, messageView);

            SDAResult res = roomService.saveKnowledgeRoomMessage(messageView);

            //todo: check if any knowledge since last message have been added into system
            int knowledgeSize = knowledgeService.getAllKnowledge().size();
            int knowledgeSizeControl = knowledgeService.getKnowledgeCount();

            if (knowledgeSize != knowledgeSizeControl) {
                log.info(
                        "change method! " + LocalDateTime.now() + " username: " +
currUser.getUsername() + " knowledge size: " +
knowledgeService.getAllKnowledge().size());
                knowledgeService.reset();
                knowledgeService.initAllKnowledge();
                processEnterRoom(false);
            }

            log.info("done!" + res.getMessage());

        } catch (SDAException e) {
            log.error("Process Message failed!" + e);
            FacesContext.getCurrentInstance().addMessage(null, new
FacesMessage(FacesMessage.SEVERITY_ERROR,
                    "Something went wrong during sending your message!", ""));
        }
    }
```

Appendix 2 Keyword Extraction in Communication (A2)

```
    private boolean checkWordUseful(String word) {
        return word.length() > 2 &&
```

```
!S
DAConstants.getStopwordsMoreThan2Digits().contains(word.toLowerCase());
    }
```

Appendix 3 Knowledge Use (A4 and A10)

```
private void processKnowledgeUse(List<MessageView> messages)
    {
        List<MessageView> contentWords = new ArrayList<>();

        for (MessageView message : messages)
            contentWords.add(new MessageView(message));

        contentWords = contentWords.stream()
                .filter(contentWordsPredicate())
                .collect(Collectors.toList());

        contentWords.forEach(w ->
w.setWord(SDAUtil.trimStringFormCharacters(w.getWord())));

        List<MessageView> finalContentWords = contentWords;
        List<MessageView> twoWordsResults =
checkTwoWordsContextInDB(finalContentWords);

        twoWordsResults
                .forEach(word -> messages.stream()
                        .filter(item ->
SDAUtil.trimStringFormCharacters(item.getWord()).equalsIgnoreCase(word.getWord()) &&
word.isFoundInDB())
                        .findFirst()
                        .ifPresent(a -> a.copyView(word)));

        finalContentWords.removeIf(word -> twoWordsResults.stream()
                .anyMatch(result ->
result.getWord().equalsIgnoreCase(SDAUtil.trimStringFormCharacters(word.getWord()))
&& result.isFoundInDB()));

        List<MessageView> oneWordResults = checkContextInDB(finalContentWords);
        oneWordResults
                .forEach(word -> messages.stream()
                        .filter(item ->
SDAUtil.trimStringFormCharacters(item.getWord()).equalsIgnoreCase(word.getWord()) &&
word.isFoundInDB())
                        .findFirst()
                        .ifPresent(a -> a.copyView(word)));
    }
```

Appendix 4 Knowledge Acquisition (A4 and A6)

```
private void processKnowledgeAcquisition(List<MessageView> messages) {

        log.info("Testing HERE!! acquisition");
        List<MessageView> contentWords = new ArrayList<>();

        for (MessageView message : messages)
```

```
            contentWords.add(new MessageView(message));

        contentWords = contentWords.stream()
                .filter(contentWordsPredicate())
                .filter(word -> !word.isFoundInDB())
                .collect(Collectors.toList());

        contentWords.forEach(w ->
w.setWord(SDAUtil.trimStringFormCharacters(w.getWord())));

        List<KnowledgeRoomMessageView> history = new ArrayList<>();

        for (KnowledgeRoomMessageView message :
getLimitedHistory(activeRoom.getHistory()))
            history.add(new KnowledgeRoomMessageView(message));

        List<MessageView> twoWordsResults =
processTwoWordsContextInHistory(contentWords, history);

        twoWordsResults
                .forEach(word -> messages.stream()
                        .filter(item ->
SDAUtil.trimStringFormCharacters(item.getWord()).equalsIgnoreCase(word.getWord()) &&
word.isFoundInUsage())
                        .findFirst()
                        .ifPresent(a -> a.copyView(word)));

        contentWords.removeIf(word -> twoWordsResults.stream()
                .anyMatch(result ->
result.getWord().equalsIgnoreCase(SDAUtil.trimStringFormCharacters(word.getWord()))
&& result.isFoundInUsage()));

        List<MessageView> oneWordResults =
processOneWordContextInHistory(contentWords, history);
        oneWordResults
                .forEach(word -> messages.stream()
                        .filter(item ->
SDAUtil.trimStringFormCharacters(item.getWord()).equalsIgnoreCase(word.getWord()) &&
word.isFoundInUsage())
                        .findFirst()
                        .ifPresent(a -> a.copyView(word)));

        // Remove all other acquired messages from control
        history.stream()
                .flatMap(message -> message.getWords().stream())
                .forEach(a-> a.setFoundInUsage(false));
    }
```

Appendix 5 Knowledge Storage (A5 and A7)

```
public String addKnowledge() {
        if (selectedCategory == null) {
            return null;
        }

        log.info("chosen category: " + selectedCategory);
        view.setDfXCategory(DfXCategory.getEnum(selectedCategory.substring(3, 6).trim()));
```

```
        view.setDfXSubCategory(DfXSubCategory.getEnum(selectedCategory));

        view.setOwnerID(personenService.getCurrUser().getUuid());

        if (stream != null) view.setFileUpload(stream);

        try {

view.setSynonyms(apiService.findSynonymsWithDataMuse(SDAUtil.trimStringFormCharac
ters(view.getWord())).getSynonyms());
            knowledgeService.saveKnowledge(view);

            FacesContext facesContext = FacesContext.getCurrentInstance();
            Flash flash = facesContext.getExternalContext().getFlash();
            flash.setKeepMessages(true);
            facesContext.addMessage("messages",
                    new FacesMessage(FacesMessage.SEVERITY_INFO, "Knowledge
successfully saved!", ""));


        } catch (SDAException e) {

            FacesContext.getCurrentInstance().addMessage(null, new
FacesMessage(FacesMessage.SEVERITY_ERROR, e.getMessage(), ""));
            log.info("Knowledge save failed!" + e);
        }

        return "home?faces-redirect=true";
    }
```

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