Designing a Black Box System for the Management of Tacit Knowledge

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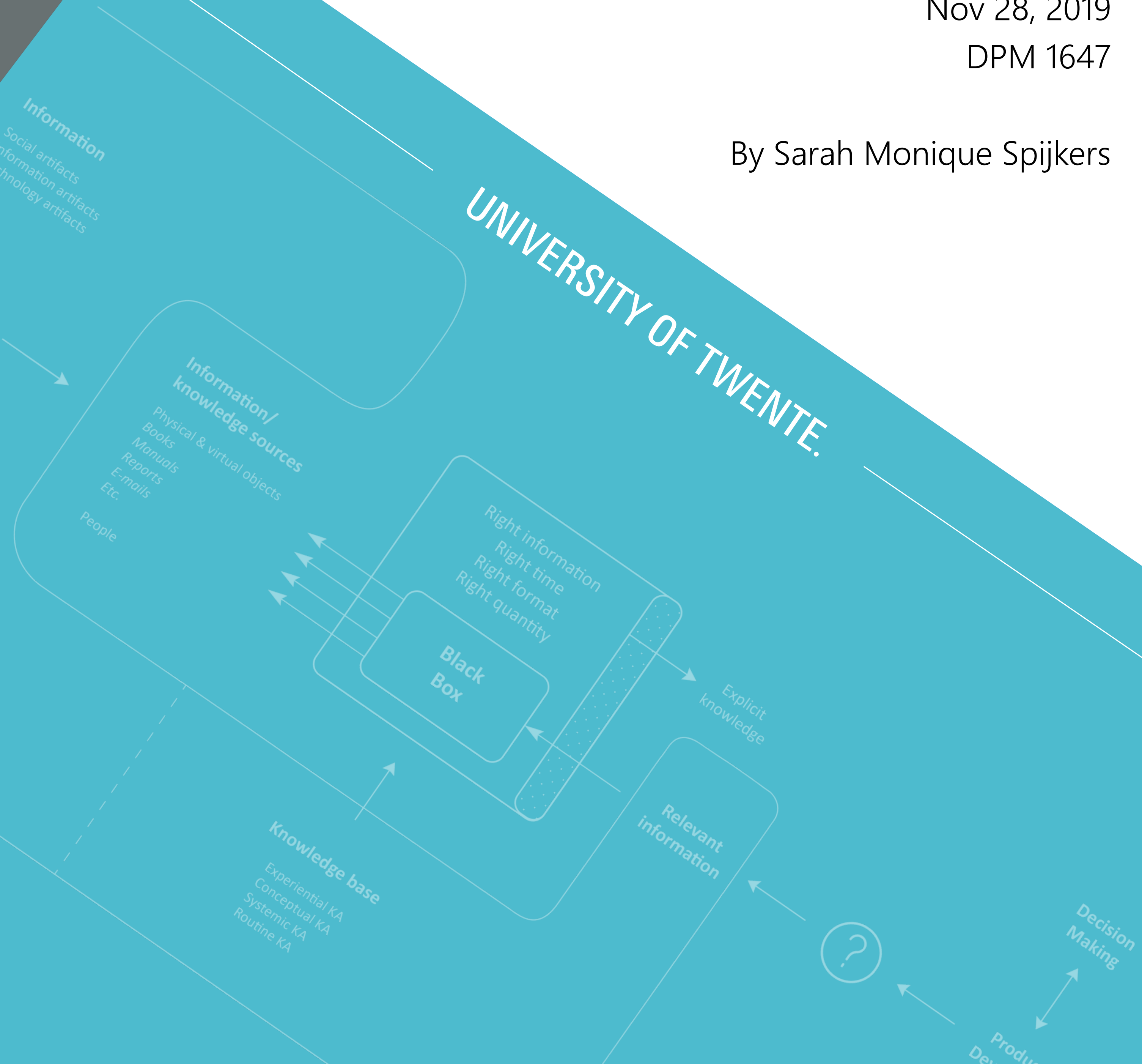

ABSTRACT

Information and knowledge have been defined as key factors in organizational decision-making and problem solving. A lot of information and knowledge arises from everyday product development activities through, for example, the execution of product development processes and the process of decision-making. This information and knowledge need to be managed and shared, but not only do they both need to be processed, new information and knowledge must also be created. This thesis firstly defines the activities that must be pursued in information-centered product development. Then, it is explained what types of information and potential knowledge are created and obtained through the activities executed during product development. This information can turn into knowledge, but also existing/current knowledge can be used to create new knowledge. This process of knowledge conversion is explained for all levels of an organization. The knowledge assets that are created (e.g. by the process of knowledge conversion) become part of the organizational knowledge base. This knowledge base includes explicitly available knowledge, but also tacit knowledge that resides in the minds of people such as experience. Tacit knowledge has been defined as an important source of new knowledge, but it is hard to manage because it is not explicitly available, and people can often not articulate it. Several techniques are provided for the management of explicit knowledge, but more importantly, this thesis provides techniques for the management of tacit knowledge. To manage tacit knowledge, a black box model is created that facilitates the management of tacit knowledge by managing knowledge sources. A division is made between tacit knowledge that resides in physical and virtual objects, and tacit knowledge that resides in people. By using a topic modeling approach, topics that are covered in objects can be identified, and these objects can be labeled accordingly. Through the creation of information profiles, it can be determined which individual has interacted with which knowledge areas. The black box system subsequently uses this information to push potentially relevant information (for example documents covering similar topics, or information profiles of people that have similar knowledge) to its users, or users can pull it from the system by using search queries. In this way, the black box system manages tacit knowledge without having to make it explicit. Moreover, it aims to reduce the feeling of information overload by providing potentially relevant information and knowledge based on topics, rather than overwhelming people with all information and knowledge that exists within an organization.

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Chapter 1: Introduction

All over the world, enterprises and organizations produce and supply goods and services for consumers to be used and enjoyed. These enterprises and organizations are part of a worldwide *manufacturing* industry that produces goods and services on a daily basis, with the goal to create products with new or different characteristics that offer new or additional benefits to the customer.[1] In order to produce these products and market them, raw materials, parts, (sub)assemblies, and final products must go through an extensive manufacturing process that makes them available to consumers.

Manufacturing industries can be classified as primary, secondary, and tertiary industries (Groover 1987). See figure 1. Primary industries are industries such as agriculture and mining. This type of industry cultivates and exploits natural resources. The outputs of primary industries are subsequently converted into products by secondary industries. Manufacturing is the principle activity in secondary industries, but this category also includes industries such as construction, food processing, and the pharmaceuticals industry. Tertiary industries constitute the service sector of the economy. This thesis is concerned with the secondary industries, which are composed of the companies engaged in the manufacturing and development of tangible products.

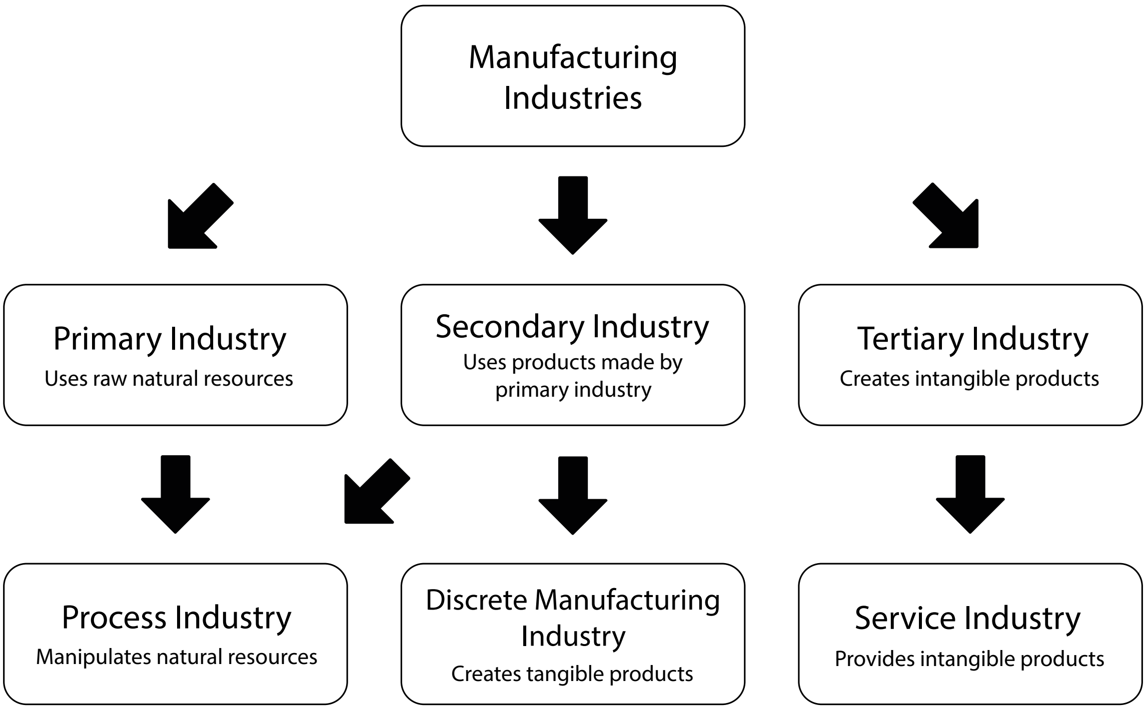


Figure 1: Industry classification

Within the secondary industry, it is important to make a distinction between the process industries and the industries that make discrete parts and products. Groover clearly explains the difference in production operations by stating that "process industries perform production operations on amounts of materials, because the materials tend to be liquids, gases, powders, and similar materials, whereas discrete manufacturing industries perform their operations on quantities of materials, because the materials tend to be discrete parts and products" (Groover 1987). In other words, contrasting to the materials that are processed by process industries, discrete manufacturing industries produce

[1] product development. BusinessDictionary.com. Retrieved from http://www.businessdictionary.com/definition/product-development.html

individual, identifiable units of material. This distinction is further emphasized by looking at the kinds of unit operations that are performed on the materials in each of the industry categories. Process industries perform operations such as chemical reactions, distillation, and heating, while discrete manufacturing industries perform operations such as casting, forging, and extrusion on its materials (Groover 1987). See table 1.

TYPICAL UNIT OPERATIONS IN THE PROCESS INDUSTRIES	**TYPICAL UNIT OPERATIONS IN THE DISCRETE MANUFACTURING INDUSTRIES**
Chemical reactions	Casting
Comminution	Forging
Deposition (e.g. chemical vapor deposition)	Extrusion
Distillation	Machining
Heating	Mechanical assembly
Mixing and blending of ingredients	Plastic molding
Separation of ingredients	Sheet metal stamping

Table 1: Typical unit operations in process and discrete manufacturing industries (Groover 1987)

The process industry includes industries from both the primary and secondary sector. Primary industries such as the petroleum industry are part of the process industry, as well as secondary industries such as the food & beverages industry and the pharmaceuticals industry (Groover 1987). Groover points out that many of the products that are made by process industries are finally sold to consumers in discrete units (Groover 1987). To support this statement, he gives examples of beverages that are sold in bottles and cans, and pharmaceuticals purchased as pills and capsules.

This research focuses on products created in discrete manufacturing industries. Thus, the scope of this thesis is directed at those industries that produce discrete, physical products. Furthermore, this thesis focuses on small and medium-sized enterprises (SMEs) within the discrete manufacturing industries. The next paragraph explains which types of products are created by discrete manufacturing industries, and which types of products are included in the scope of this thesis.

Chapter 1.1: Type of Good

To further elaborate upon product development and what it entails, a division is made between the types of products that are created or manufactured by an organization. Final products made by discrete manufacturing industries can be divided into two major categories: industrial/capital goods and consumer goods (e.g. (Groover 1987, Avlonitis and Gounaris 1997, Kohli 1997, Jones and Mendelson 2011)). Industrial or capital goods are goods for industrial and business use. They are purchased by other companies to produce goods and supply services. This type of product consists of, among others, the machinery that produces the final goods or end products that are used by consumers, but also commercial aircraft and railroad equipment (Groover 1987). Therefore, the demand of this type of product is usually based on the demand for the products they (help) produce.[2] Industrial goods can be classified into two categories: production goods and support goods. Production goods are used in the production of a final product; examples of production goods are raw materials and components. Support goods help in the production process of a final product; examples of support goods are machinery and equipment. The industrial goods sector includes companies involved with, amongst others, defense, aerospace, and construction.

Consumer goods are the final goods or end products that are produced by industrial goods. Consumer goods are purchased directly by consumers to satisfy their needs and desires. Consumer goods can be classified into three types of products: durable goods (e.g. cars, furniture), non-durable goods (e.g. food and beverages, clothing) and consumer services (e.g. car repair, mail delivery) (Tarver 2015). Based on buying patterns, consumer goods are typically classified into four categories: convenience goods, shopping goods, specialty goods, and unsought goods (Tarver 2015). Convenience goods are products such as food, beverages, cigarettes and medicine. By nature, this type of product is often non-durable. In contrast to convenience goods, shopping goods are products that require more planning and thought of the consumer during the purchasing process. Examples of shopping products are furniture, electronics, and electric appliances. Specialty goods are products that are deemed to be luxuries; jewelry, high-fashion clothing, and professional photographic equipment are represented by this category. Lastly, unsought goods are products or services that consumers are not aware of or have no knowledge about. Even if the consumer has knowledge of such products, they are not bought under normal circumstances because of a perceived lack of tangible benefits. Services that fall into this category are funeral services and life insurance. Some important differences between industrial goods and consumer goods can be found in table 2.

As mentioned, the scope of this thesis is directed at those industries that produce discrete, physical products. Although there are many companies in this industry whose business is primarily to produce materials, components, and supplies for the companies that make final products (through unit operations as can be seen from table 1 on p.2), this thesis focuses on the creation of final products for consumers i.e. consumer products.

[2] This is known as derived demand. Derived demand is solely related to the demand placed on a good or service for its ability to acquire or produce another good or service.

	INDUSTRIAL GOODS	CONSUMER GOODS
DEMAND	Derived, inelastic	Direct, elastic
BUYING MOTIVE	Purchased for making other products	Purchased for personal consumption
BUYING POWER	Rational	Emotional
PRODUCT LINES	Complex	Relatively Simple
PURCHASE VALUE	High	Low-Medium
LEVEL OF INVESTMENT	High	Low-Medium
NUMBER OF BUYERS	Small	Large

Table 2: Industrial goods vs. consumer goods

Chapter 1.2: Method of Production

In order to produce and realize products, components and assemblies that compose these products must go through a sometimes very extensive manufacturing process. As described in DIN 8580, manufacturing processes can be classified into six main groups, based on the changes in the cohesion of the workpiece material (Kals, Buiting-Csikós et al. 2016). These six categories are primary shaping, material forming, dividing and material removal, joining, modification of material properties, and coating. Although these processes are very interesting, explaining these processes does not fall within the scope of this thesis. For more information about these processes, see e.g. (Kals, Buiting-Csikós et al. 2016). For this research, production activity is classified according to the quantity of product that is made. Based on (Kals, Buiting-Csikós et al. 2016), the three production/manufacturing types that are referred to are single-piece production, batch production, and mass production.

Single-piece production or manufacturing (also called single parts manufacturing, job production/ one-off production, small batch manufacturing, or project-based manufacturing) is the manufacture of very small numbers of products (Kals, Buiting-Csikós et al. 2016). With single-piece manufacturing, single (often unique) items are made individually, and each item is finished before the next one is started. This type of production method often relies heavily on the skills and flexibility of an organization's employees, as products are made according to individual customer needs. Depending on the type of product being manufactured, there can be a large difference in set-up costs and capital intensity. For example, when building a ship, the set-up costs and capital intensity will be significantly higher than for creating a tailor-made suit.

Batch production or manufacturing is concerned with the creation of successive one-off product batches with a finite amount or quantity of material (Groover 1987, Kals, Buiting-Csikós et al. 2016). With batch production, several identical products (ranging from a few to thousands of units) are processed, usually one at the time rather than altogether at once (Groover 1987). The products that are created may vary from batch to batch, but the products within a batch are (virtually) identical. Batch production is a non-continuous process, as each batch is finished before starting the manufacture of the next batch of products. This causes interruptions in production between batches. See figure 2. In contrast to single-piece manufacturing, batch manufacturing produces a higher number of products and therefore has lower unit costs and lead times. Similar to single-piece manufacturing, there can be a large difference in set-up costs and capital intensity depending on the type of product that is being manufactured. As such, the creation of baked goods in a bakery requires less set-up costs and less capital than the manufacture of computer chips.

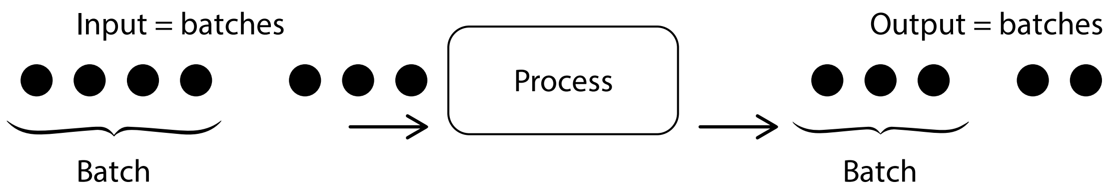


Figure 2: Batch production in discrete manufacturing industries (Groover 1987)

Figure 3: Continuous production in discrete manufacturing industries (Groover 1987)

Mass production or manufacturing (also called flow production or continuous production) is the production of very large batches of products (ranging from hundreds to millions of units) in long periods of time (ranging from months to years) (Kals, Buiting-Csikós et al. 2016). Mass production produces identical, relatively simple products that are standardized and offered in a small variety. This type of production method forms a continuous process, meaning that production equipment is used exclusively for the given product and the output of the product is uninterrupted (Groover 1987). Moreover, productivity is high with this method of production because there are no breaks for product changeovers (Groover 1987). See figure 3. In contrast to single-piece manufacturing and batch manufacturing, mass production creates by far the highest number of units in a given period of time. Therefore, in contrast to previously mentioned production methods, mass production has the lowest unit costs and lead times. Because mass production is very capital intensive, it does not require many skills and knowledge from an organization's employees.

Table 3 summarizes some important differences between the three types of production methods (in relation to each other) explained in this paragraph.

	SINGLE-PIECE PRODUCTION	**BATCH PRODUCTION**	**MASS PRODUCTION**
DEMAND	Low	Medium	High
NUMBER OF UNITS	Low	Medium	High
UNIT COSTS	High	Medium	Low
LEAD TIMES/ PRODUCTIVITY	High/Low	Medium-Low/ Medium-High	Low/High
SET-UP COSTS	Low-High	Medium-High	High
CAPITAL INTENSITY	Low-High	Medium-High	High
LABOR INTENSITY	High	Medium	Low
LABOR SKILL	High	Medium	Low
LABOR COSTS	High	Medium	Low
ORGANIZATION	Project specific	Process specific	Product specific

Table 3: Differences between single-piece production, batch production, and mass production

This thesis focuses on discrete manufacturing industries that develop/manufacture physical consumer products. This research does not focus on one particular method of production; however, the production method must produce enough information to require the use of an information management system. For example, a freelancer that produces tailor-made products through single-piece manufacturing might not benefit from an information management system, because the amount of information that this person deals with is not necessarily managed (more) efficiently by an information management system. Therefore, applicability/relevance must be determined per situation.

Chapter 1.3: Motive & Objective

In today's information age, information is abundant in many organizations and expands daily (Uys, Du Preez et al. 2008). This information must be managed and shared to make it more valuable to an organization (Cruz, Boster et al. 1997). Moreover, having access to the right information at the right time is of pivotal importance in decision-making and problem solving (Sharda, Frankwick et al. 1999, Ada and Ghaffarzadeh 2015), but also to accomplish objectives such as innovation (Uys, Du Preez et al. 2010). To achieve these objectives, many companies and organizations have developed and currently use information (management) systems to facilitate the dissemination of information. These systems focus on the dissemination of explicit knowledge, which is knowledge that is explicitly available. Examples of explicit knowledge include documents, drawings, and best practices (Sanchez 2005), but also legally protected intellectual properties such as licenses and patents (Nonaka, Toyama et al. 2000).

Although information systems can be very useful in managing information within an organization, they also have some disadvantages and shortcomings. Often, it seems to be forgotten that connectivity alone does not guarantee the sharing of information over time (Sharda, Frankwick et al. 1999). Moreover, even though information is of key importance to organizations, too much information can cause information overload (e.g. (Sharda, Frankwick et al. 1999, Edmunds and Morris 2000)). Information overload is a problem many individuals and organizations suffer from (Teece 2000) and can cause problems in decision-making and problem solving by posing a threat to aspects of knowledge quality such as relevance (Sharda, Frankwick et al. 1999). In addition, too much attention is paid to explicit knowledge, leaving out a very important *tacit* aspect of knowledge. Even though tacit knowledge has been identified as a rich source of new knowledge (e.g. (Nonaka and Takeuchi 1995)), many organizations focus on managing readily available information instead of the harder to manage tacit counterpart. Moreover, because knowledge assets cannot be readily bought and sold, Teece mentions that "the market for know-how is far from complete, and where it exists it is far from 'efficient'" (Teece 2000).

Regulating the information flow and managing both explicit and tacit knowledge are important objectives that should be pursued by every organization. Because information is seen as the key to success for organizations (Edmunds and Morris 2000), information must be regulated to avoid the feeling of information overload. By providing people with an overwhelming amount of information from many different sources, the quality of a decision or solution may actually decline (Sharda, Frankwick et al. 1999). Moreover, information overload can lead to stress, los of job satisfaction and physical ill health (Lewis 1996). Edmunds and Morris state that "the problem of information overload is obviously not going to recede and solutions need to be found to enable people to reduce the amount of information overload they experience" (Edmunds and Morris 2000). In addition, managing explicit and tacit knowledge is of pivotal importance now that physical assets no longer provide a source of significant differentiation (Teece 2000). Teece adds that "development, ownership, protection and astute utilization of knowledge assets, not physical assets, provides the underpinnings for competitive advantage in the new economy" (Teece 2000). Moreover, he states that "there is both the need and opportunity to match information and knowledge requirements with availability" (Teece 2000).

In conclusion, management of both tacit and explicit knowledge assets is very important for individuals as well as organizations. By managing knowledge assets in a more efficient and effective way, the feeling of information overload might be reduced, which can subsequently lead to better decision-making and problem solving. Moreover, it stimulates knowledge creation and knowledge sharing, which are key to obtaining and maintaining competitive advantage.

Objective

The objective of this thesis is twofold. In the first place, I want to design a system that provides users with relevant information, instead of providing them with all information at once. The goal here is not only to reduce the feeling of information overload, but also to stimulate efficiency and effectiveness by reducing the time one is searching for relevant information. Secondly, I want to design a system that provides users with tacit knowledge. Explicit knowledge is not excluded, but the focus is on managing tacit knowledge. Tacit knowledge is a rich source of new knowledge, but it is very hard to manage without making it explicit. However, by making tacit knowledge explicit, it loses much of its intrinsic meaning and value. Thus, the goal here is to create a system that manages tacit knowledge without having to convert it into an explicit form. By combining the two objectives, the overall goal of this thesis is to design a system that provides users with relevant tacit knowledge.

Structure of the thesis

This thesis consists of seven chapters. Chapter one provides and introduction to the research topic and explains the scope of this thesis. Chapter two provides an overview of activities that must be focused on during (information-based) product development. It describes the process-related activities needed to develop and create a product and focuses on the activities related to decision-making and information management. Chapter three explains which types of information arise during the activities performed in chapter two, and how knowledge may be derived from this information. Chapter four explains the types of knowledge that are obtained during product development, and how this knowledge can be converted and shared to obtain and create new knowledge. Knowledge is created at all levels of an organization; therefore, this chapter describes how knowledge can be converted at each level of an organization. Chapter five describes how information and knowledge, and in particular tacit knowledge, can be managed by an organization. A black box model is proposed that manages tacit knowledge by using explicit knowledge of where tacit knowledge might be found. Chapter six subsequently explains the functionality of this black box system. Chapter seven concludes this research by providing an overall conclusion and recommendations for implementation. Figure 4 provides an overview of the subjects discussed in this thesis (a larger image is available on the next page).

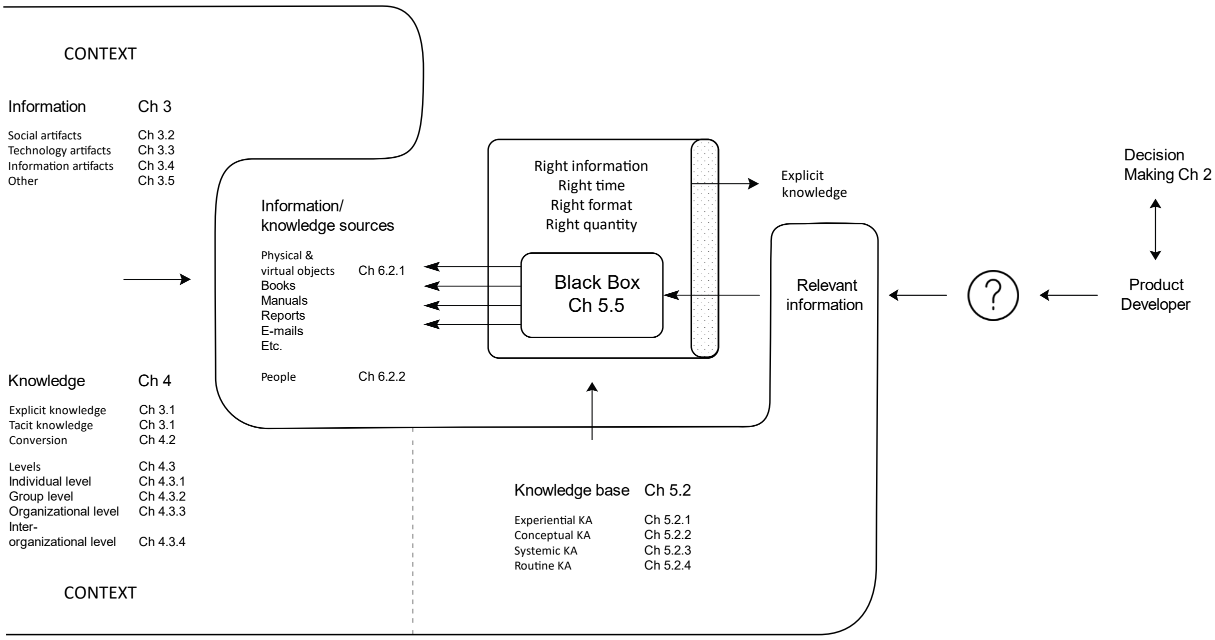
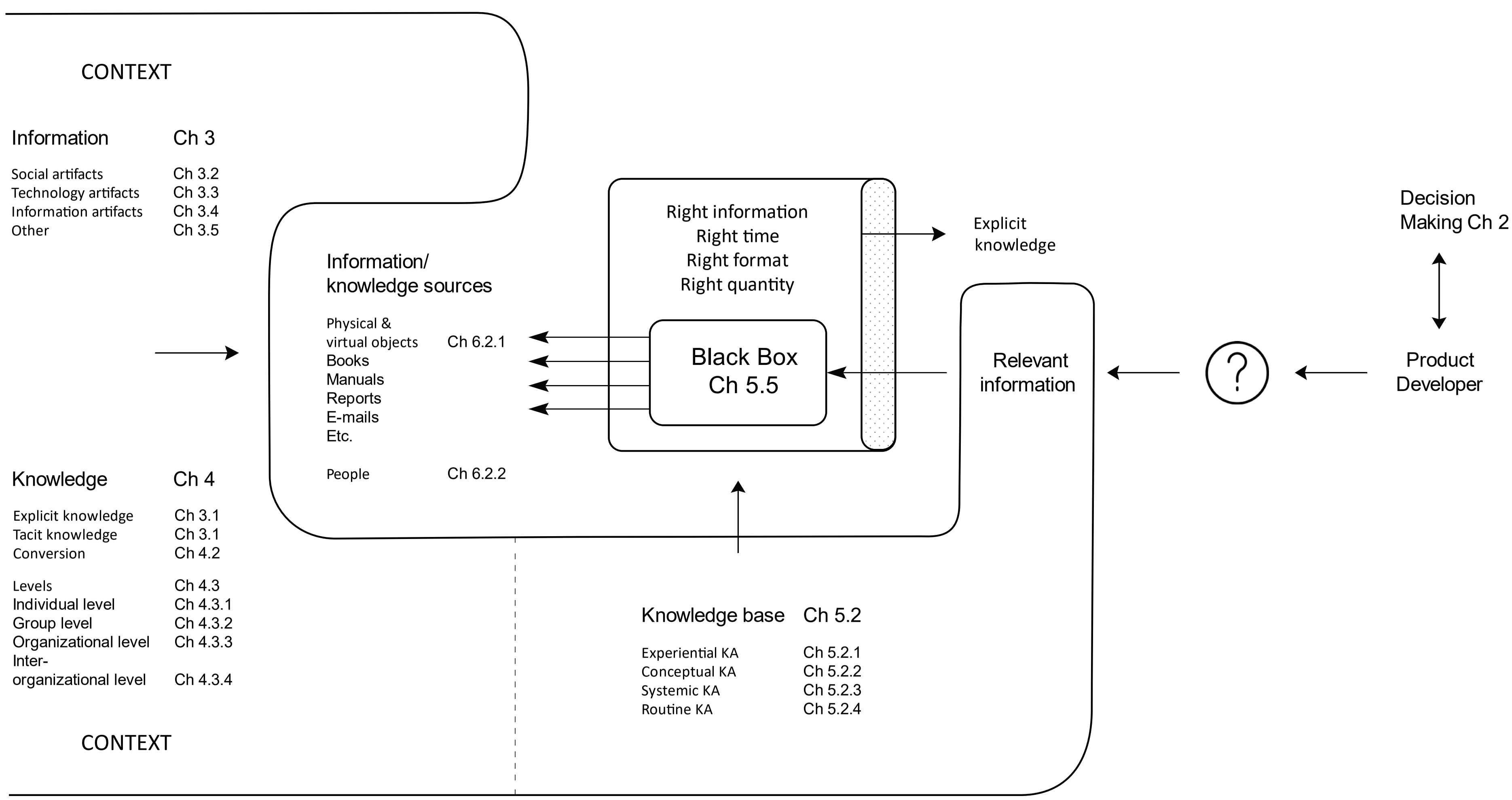


Figure 4: Overview of thesis including corresponding chapters


CONTEXT
Information Ch 3
Social artifacts Ch 3.2
Technology artifacts Ch 3.3
Information artifacts Ch 3.4
Other Ch 3.5
Knowledge Ch 4
Explicit knowledge Ch 3.1
Tacit knowledge Ch 3.1
Conversion Ch 4.2
Levels Ch 4.3
Individual level Ch 4.3.1
Group level Ch 4.3.2
Organizational level Ch 4.3.3
Inter-organizational level Ch 4.3.4
CONTEXT
Information/ knowledge sources
Physical & virtual objects Ch 6.2.1
Books
Manuals
Reports
E-mails
Etc.
People Ch 6.2.2
Right information
Right time
Right format
Right quantity
Black Box
Ch 5.5
Explicit knowledge
Knowledge base Ch 5.2
Experiential KA Ch 5.2.1
Conceptual KA Ch 5.2.2
Systemic KA Ch 5.2.3
Routine KA Ch 5.2.4
Relevant information
?
Product Developer
Decision Making Ch 2

Chapter 1.4: Method of Development

In literature and practice, a wide variety of design and development models can be found. Design or development models prescribe the activities that must be executed to develop a product and are used to maintain an overview over a process and steer that process in the right direction (Dankers and Lutters 2010). In addition to clarifying the necessary activities, they also prescribe the sequence in which they must be executed (Dankers and Lutters 2010). Often, these activities are grouped into different phases. These type of models are prescriptive in nature and are mostly suitable for routine projects (Dankers and Lutters 2010). Currently, product development mostly relies on these types of process-oriented or process-based models. This method of development, which can also be called *process-based* development, is based on the processes that are associated with a product's development. Employing this method of product development often means that given or predefined steps are executed in a logical sequence of phases or events. This method of development assumes that following the prescribed process results in better designs. Many variations of process-based design and development models exist. Examples of well-known process-based design and development models are the product development process model by Pahl and Beitz (Pahl, Beitz et al. 2007), the design process model by Koller (Koller 1985), the integrated product development process model by Andreasen (Andreasen and Hein 1987), and the design process model by Ullman (Ullman 2002). See figures 5, 6, 7, and 8 respectively. Which model is most suitable for a certain development trajectory depends on organizational and project characteristics (Dankers and Lutters 2010).

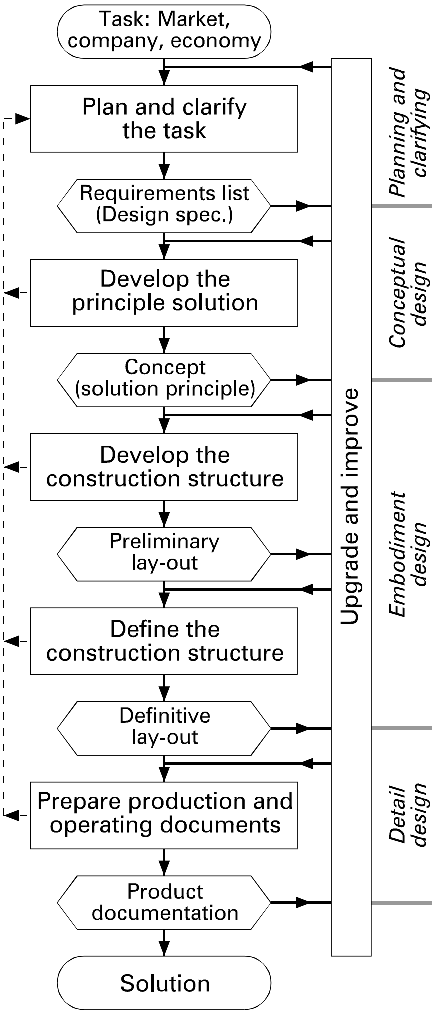


Figure 5: Pahl and Beitz's development process

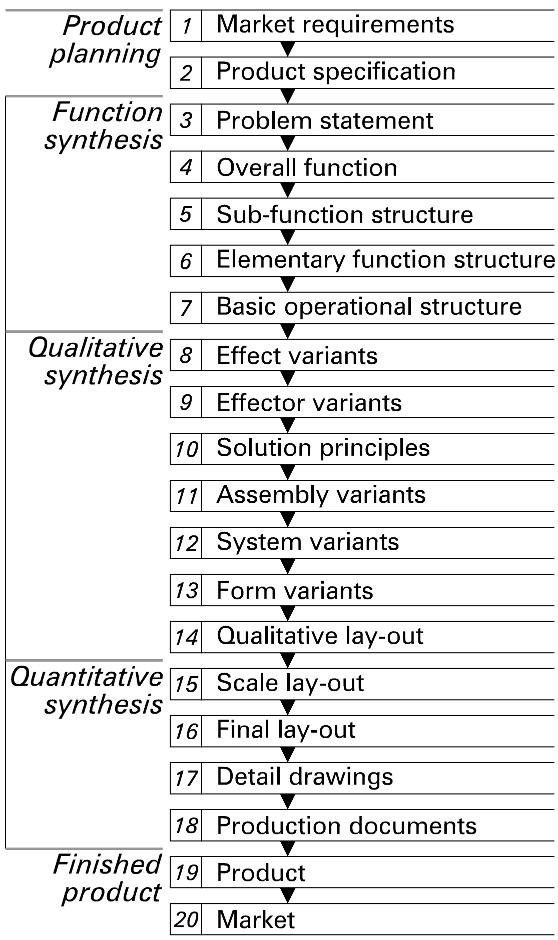


Figure 6: Koller's design process

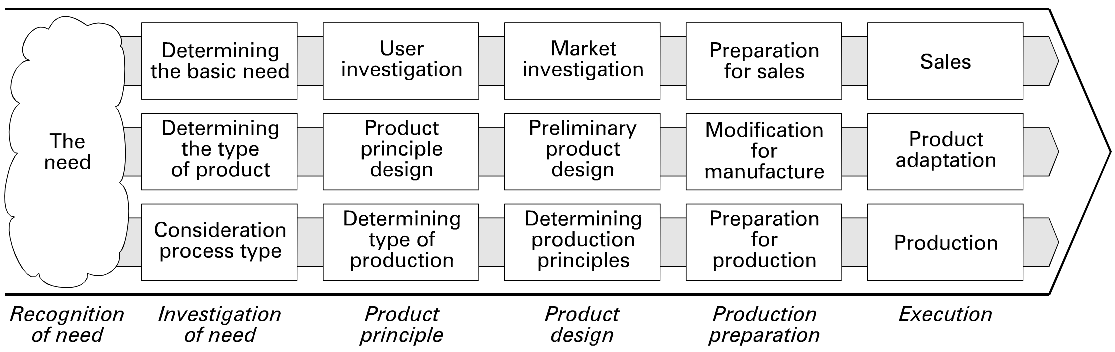


Figure 7: Andreasen's integrated product development process (Andreasen and Hein 1987)

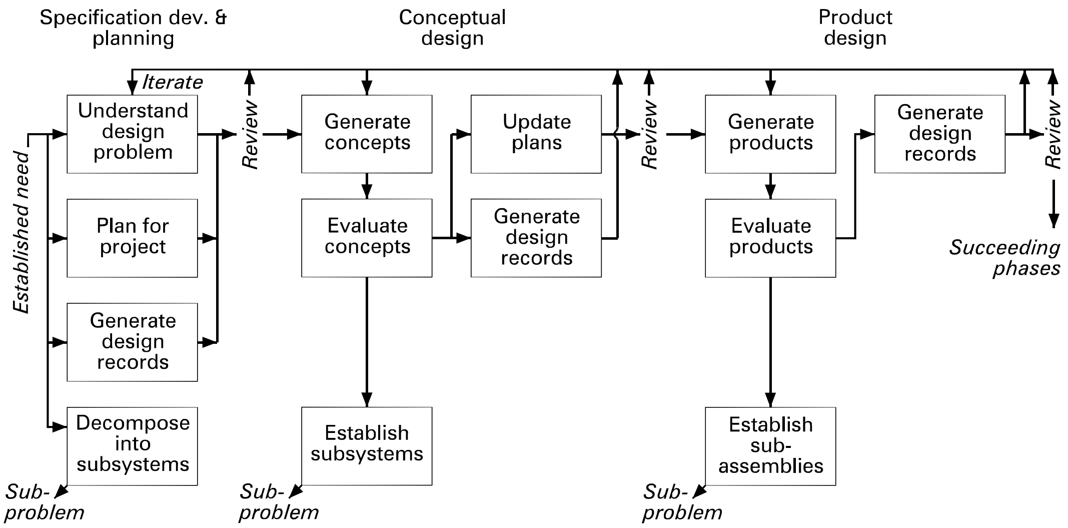


Figure 8: Ullman's design process (Ullman 2002)

The design model created by Pahl and Beitz is one of the most well-known design models used in industry and education (Tomiyama, Gu et al. 2009). The model is divided into four sequential, functionally dependent phases, which are planning and clarification of tasks, conceptual design, embodiment design, and detail design (see figure 5). A model that is very similar to this model is the design model created by Roth (Roth 1982). See figure 9. In contrast to Pahl and Beitz's model, Roth's model does not include the activities that are to be executed after the completion of the design. Similarly to the design model created by Pahl & Beitz and Roth, Koller created a model that defines multiple phases and the tasks or activities that should be executed within these phases. See figure 6. A very important difference between the two design models is that the model created by Pahl and Beitz incorporates iteration, and the model created by Koller does not. Like Pahl and Beitz, Roth, and Koller, Andreasen created a model that makes a distinction between the phases in product development and the processes that should be executed in these phases (see figure 7). However, Andreasen relates these processes to three different aspects of development, which are market, product, and production. Andreasen's model does not incorporate iterations, in contrast to Ullman who emphasizes iteration by creating a review moment after every phase (see figure 8). When comparing the five models, it can be observed that all models show the (functionally dependent) phases involved in the product design or development process, and then break down these phases into activities. For the models created by Pahl and Beitz, Roth, and Ullman, iteration is possible at the end of the conceptual (i.e. functional) and embodiment (i.e. form design/product design) phases. All models are very similar in nature, but they each focus on different product types, manufacturing environments, and aspects of the development cycle (Tomiyama, Gu et al. 2009).

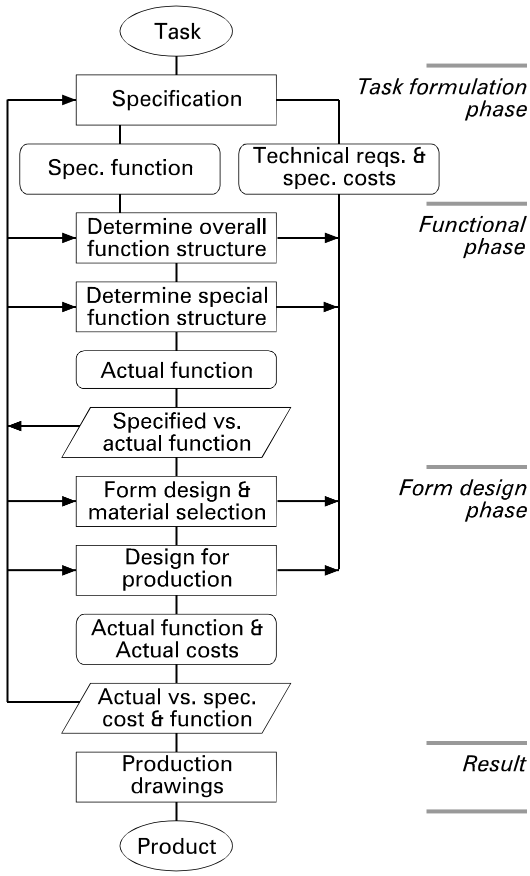


Figure 9: Roth's design process (Roth 1982)

There are some general limitations regarding all design and development models, independent of the overall suitability of a model. Dankers and Lutters (Dankers and Lutters 2010) mention several limitations, of which a few are explained in more detail. Firstly, Dankers and Lutters mention limitations regarding lack of flexibility and suitability. A model that prescribes activities can be very restricting and might be confusing because one cannot foresee all potentially required processes and activities that are needed to develop a product. Moreover, they mention that a model cannot be generic and meticulous at the same time. Although many models try to do exactly that, many variations exist because a model (either generic or specific) cannot be adequate or suitable to every situation. Secondly, Dankers and Lutters mention limitations regarding information and context information. Process steps that are determined based on insufficient, incomplete, unreliable, or non-unique interpretable information may not provide adequate support or any support at all. Moreover, by focusing on processes, the subject matter that is created by these processes is oppressed. Thirdly, Dankers and Lutters mention limitations regarding decision-making. Although some models focus on decision-making, none explicitly incorporates decision-making activities. Given the fact that decisions do not only influence the design of a product, but also future activities regarding manufacturing (Dankers and Lutters 2010), it is notable that none of these models explicitly mentions decision-making. Lastly, it should be noted that none of these widely accepted models focuses on information management, or what is possibly more important, knowledge creation. When information that is created and used in a development cycle is not managed in an efficient and effective manner, it is hard to reuse it and obtain knowledge from this information. Overall it can be said that, in case of routine projects, a strict and prescribing development method would probably offer adequate support. For the development of comparable products, it is then possible to determine which process(es) will probably be most efficient and effective to use. However, when developing (radically) innovative products, this development method will not offer adequate support or, at worst, not offer any support at all. Thus, another method of development is needed that solves the limitations regarding process-based product development. To achieve this, an approach must be sought that focuses less on processes and more on the product itself, the information content regarding the product, and decision-making. This is where information-based or information-centered product development can be of great importance. In contrast to process-based development, information-based development focuses on the value of information (content) of the product itself, rather dan on the processes that are needed to create a product (De Lange 2018). Information-based development focuses on the product; however, until a product is manufactured into a physical product, the product (or the idea/concept of the product) consists of information regarding that product such as problem statements, product drawings, requirement specifications, and many more. This (product) information is the main focal point of information-based product development. Now, processes can be used to achieve a change in information content, i.e. the processes can be used to 'transform' information of one kind into information of another kind (Lutters 2001). By employing this method of development, product development activities are logically deduced from the evolving information (content) and the evolving product, rather than from the expected activities associated with a product's development (De Lange 2018). See table 4.

	PROCESS-BASED DEVELOPMENT	**INFORMATION-BASED DEVELOPMENT**
BASED ON	Processes	Product
MAIN FOCUS	Execution of phases	Changing of product/ information content
ACHIEVED BY	Performing activities	Decision-making
GUIDED BY	Design and development models	Information content
METHOD	Prescriptive	Descriptive
FLEXIBILITY	Low	High

Table 4: Process-based development vs. information-based development

This information-centered approach has several benefits of which a few are highlighted. Firstly, information-based product development creates flexibility in design and development activities. When the (evolving) information content of a product is used to steer the development process, following prescribed processes is no longer necessary. Instead, the processes can be used to achieve a desired change in information content. In this way, the evolving product steers the processes rather than the other way around. This perspective of development thus creates flexibility in development activities and (partially) eliminates the need for prescriptive process models. Secondly, this method of development incorporates and focuses on (context) information. Context information is important to obtain knowledge. As Teece puts it: "knowledge is not primarily about facts and what we refer to as 'content'; rather, it is more about 'context'" (Teece 2000). In this sense, information provides the content, and knowledge serves as context. Together, they can enable knowledge creation and better decision-making. Thirdly, in contrast to process-based development that does not generate adequate information in the backward transformation mode (Lutters 2001), information-based development facilitates backward information transformation. This means that the influence of any downstream modification of earlier made design, engineering and planning decisions can be investigated (Lutters 2001) and information transformations (i.e. transformation of information from one state to another state, such as the transformation of product information to manufacturing instructions) can be analyzed. In this way, information-based development focuses on decision-making by using it as a tool to transform the information content.

Chapter 2: Activities in Information-Based Product Development

Chapter 2.1: Introduction

The previous chapter has explained the difference between information-based product development and process-based product development, and why the former is preferred over the latter. Information-based development can be divided into three categories of activities: activities regarding the processes of product development, decision-making, and information management activities. Development processes are necessary to create and produce products; though, in contrast to process-based development, these processes are not regarded as the driving factor in information-based product development. A general description of processes required to develop a product is given based on the product life cycle. The process of decision-making is viewed as an independent activity, as decision-making is regarded as an essential element throughout a product life cycle. Information management activities are necessary to manage the information that information-based product development focuses on, and potentially create new knowledge based on (the management of) this information. This chapter elaborates upon these three categories of activities and explains how they contribute to information-based product development.

Chapter 2.2: Product Development Processes

As explained in chapter 1, product development is about the creation of new products and services, or the modification of existing products and services. In addition, it has been mentioned that this thesis focuses on the creation of physical consumer products. In order to create or modify tangible products, activities and processes need to be executed by people and equipment. During product development, and during a product life cycle in general, many processes are performed to achieve a desired result. This paragraph explains some of these activities based on the product life cycle, and shows them from three perspectives, or *mindsets*, of product development.

Chapter 2.2.1: The Product Life Cycle

From a broad perspective, development of physical products can be divided into four product life cycle phases: research and development (R&D), realization, use, and disposal. See figure 10.

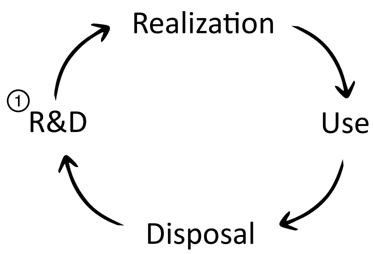


Figure 10: A simplified product life cycle model

This division is based on the well-known life cycle model created by Pahl and Beitz (Pahl, Beitz et al. 2007). See figure 11. Tomiyama et al. mention that this model is by far the most known and used model in both industry and education and often serves as a reference (Tomiyama, Gu et al. 2009). As can be seen from figure 11, this method places design as a central activity of the whole product life cycle.

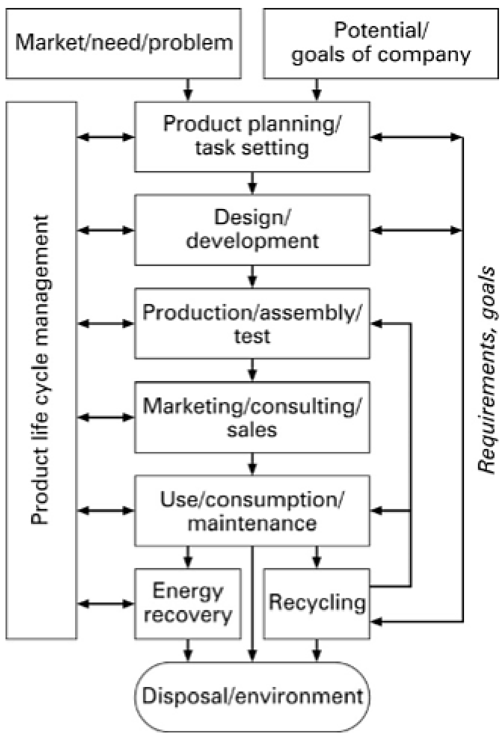


Figure 11: Life cycle model by Pahl and Beitz (Pahl, Beitz et al. 2007)

The first phase, as depicted in figure 10 by the number 1, is the research and development phase. This phase is concerned with research and development activities that help to develop new products, or research ways of improving already existing products or processes (Hall 2006). The goal of this phase is to gain competitive advantage and stay profitable through innovation (Nobelius 2004). From an information-centered perspective, it can be phrased as "the creation of a new body of knowledge about existing products or processes, or the creation of an entirely new product".[3] This definition emphasizes knowledge in the development and improvement of (new) products and processes. According to the concept of design thinking (see chapter 2.2.2), research and development processes can be subdivided into five consecutive stages, which are the 'emphasize' mode, the 'define' mode, the 'ideate' mode, the 'prototype' mode, and the 'test' mode. See figure 12. The concept of design thinking and the different modes are further elaborated upon in chapter 2.2.2.

A lot of information and knowledge is generated in this phase of product development. Examples of information and knowledge generated in this phase are customer knowledge obtained through market research such as brand equity and brand identity, and several kinds of product knowledge such as product application and features, use and support requirements, and customer experience. This knowledge is mainly obtained through experience (see chapter 3.5.2) and can be used to enhance future research and development activities.

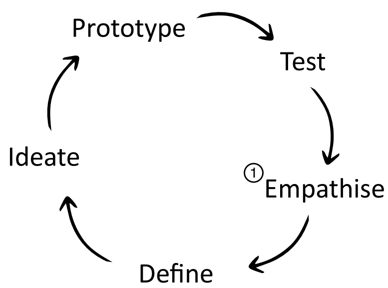


Figure 12: The five stages of research and development based on design thinking

The second phase, which is the realization phase, is concerned with activities needed to realize a product. When a new solution has been developed and (prototype) tested, it must be realized in order to market it. Realization is not a straightforward process; although a product has been developed and tested, a lot of time and effort goes into actually building and realizing the product, and into determining how a product can be realized in the most efficient way. This is an iterative process that gradually improves the product and the process through which it is realized. See figure 13. When the desired result has been reached, the product is built, revised, and improved when necessary. A lot of information and knowledge regarding the product and its development process is created through product revision, reflection, and evaluation.

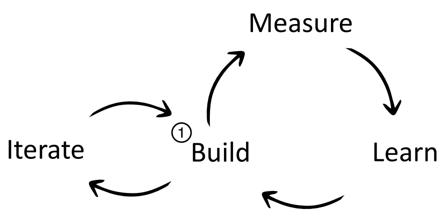


Figure 13: Product realization processes

[3] Cleverism, 'Research and Development (R&D) I Overview & Processes', 2014, Retrieved from https://www.cleverism.com/rd-research-and-development-overview-process/

The third phase, which is the use phase, is concerned with the use of the realized product by the consumer. The use phase of a product can be divided into four product life cycle stages, which are introduction, growth, maturity/stabilization, and decline. See figure 14. The product is launched in the introduction stage. Growth usually refers to growth in sales and profits. A lot of information regarding customer experience and customer knowledge is obtained during this stage. During the maturity stage, the product is established. Organizations must find a way to maintain market share and ensure future success by, for example, modifying the product or improving the production process. Information and knowledge that are obtained during the growth stage can aid in this purpose. Once product sales start to fall or profitability can no further be maintained, the decline stage is reached. The use phase of a product covers all information that arises from these product life cycle stages. This information can be, for instance, customer satisfaction and user experience, but also product use information such as information obtained through sensors and customer feedback.

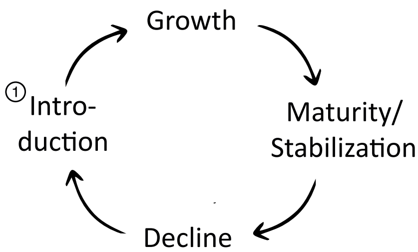


Figure 14: Product life cycle stages

The last phase, which regards the disposal phase, includes activities concerning the collection, transport, treatment, and disposal of waste. See figure 15. This collection of activities is called 'waste management' or 'waste disposal'. In this thesis, the disposal phase is regarded as a separate phase within product development. Oftentimes, R&D and realization are executed by the same product development company and waste management is handled by a different company (of course there are exceptions such as R&D institutions that focus solely on R&D, or organizations that collect waste for reuse). Because it is regarded as a different/separate sector, less attention is paid to this phase.

In addition to the physical activities of waste disposal, waste management is also concerned with the monitoring and regulation of waste management processes. Information that arises from this phase can improve the waste management process as well as the product development process by providing feedback to product developers regarding these processes. As a consequence, product developers can use this information to, for example, develop products that produce less waste, or develop products that are more easily disposable by reusing or recycling them.

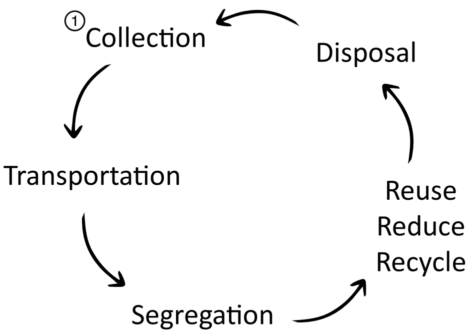


Figure 15: Waste management process

Chapter 2.2.2: Three Mindsets of Product Development

Design thinking, lean, and agile are prominent mindsets in organizations (Schneider 2017). These mindsets are not mutually exclusive; in fact, they should be combined to achieve the right outcome (Schneider 2017). A general description of the three mindsets is given below.

Firstly, design thinking is a way of thinking that aims to discover innovative strategies and solutions through intentional and repeated divergence and convergence (Schneider 2017). In contrast to being technology-centered or organization-centered, design thinking is a human-centered approach to problem solving (Brown 2008, Kimbell 2011). Design thinking can be viewed as a cognitive style, as a general theory of design, and as an organizational resource (Kimbell 2011). For design thinking as a cognitive style, its design purpose is problem solving, while for design thinking as an organizational resource, its design purpose is innovation (Kimbell 2011). For design thinking as a general theory of design, its design purpose is taming wicked problems (Kimbell 2011). Wicked problems are described by Churchman as a "class of social system problems which are ill-formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing" (Churchman 1967). Based on this definition, most problems addressed by designers are wicked problems.

Design thinking as a process is often divided in several phases. According to Brown, design projects must pass through three phases: *inspiration*, i.e. what motivates the search for a solution, *ideation*, the process of generating and creating ideas that may lead to a solution, and *implementation*, i.e. creating and manufacturing the solution in order to market it (Brown 2008). Another well-known model for design thinking that incorporates these phases is created by Stanford d.school.[4] Stanford d.school proposes a five-phase model for design thinking that consists of the following modes: the *empathize* mode, the *define* mode, the *ideate* mode, the *prototype* mode, and the *test* mode. See figure 12 on p.17. In the empathize mode, designers empathize with their target audience and create an understanding of their way of thinking and their needs and desires. In the define mode, a meaningful and actionable problem statement is created regarding the users' needs, their problem, and obtained insights. In the ideate mode, ideas are generated by challenging assumptions and focusing on innovation. In the prototype mode, designers start to create solutions through (rapid) prototyping in order to receive valuable feedback from users and colleagues. In the test mode, solutions are tested and refined. It should be mentioned that these five phases are not always to be executed in a sequential manner; the model proposed by d.school is not a hierarchical or step-by-step process. It rather serves as an overview of phases that will contribute to an innovative project.

Secondly, lean thinking is a customer-centered mindset that focuses on the identification of value, the elimination of waste, and the generation of flow (Melton 2005). According to Shah and Ward, the goal of lean production is to "create a streamlined, high quality system that produces finished products at the pace of customer demand with little or no waste" (Shah and Ward 2003). Therefore, lean production is often associated with practices such as JIT/continuous flow production, lot size reductions, quick changeover techniques, pull system/Kanban, total quality management, and so on (Shah and Ward 2003). Although lean thinking is popular in improving production processes, it has been applied to all aspects of the supply chain, including design (Melton 2005). Melton defines three principles of lean thinking, which are the identification of value, the elimination of waste, and the generation of flow (Melton 2005). Identification of value considers the creation of value propositions with regard to an organization as well as their customers (Melton 2005). Without an understanding of the needs and desires of one's customers, one cannot attach value to a product or the processes that

[4] Stanford d.school is a hub for innovation, collaboration and creativity a Stanford University.

create this product. Moreover, without the identification of value, the identification of waste is impossible. Waste can be defined as “any activity in a process which does not add value to the customer” (Melton 2005). Melton defines seven types of waste, which are over production, waiting, transport, inventory, over processing, motion, and defects (Melton 2005). Waste cannot always be eliminated; although an activity might not add value to the customer, it might add value to the company (e.g. financial controls) (Melton 2005). Although a company might not be able to eliminate all waste, it should strive to realize waste reduction and eventually achieve a waste-free process; this continuous improvement of processes is the basis for lean thinking (Melton 2005). This is consistent with information-based development that tries to eliminate activities that do not add value to a product and its evolving information content. In other words, contrasting to process-based development, information-based development does not simply follow a predefined sequel of activities of which some activities might be waste (because they are determined on beforehand, there is a high chance that some activities are unnecessary or non-value adding), but it determines the development activities based on the evolving information content of a product. Finally, when value and waste are identified, it must be ensured that value is flowing to the customer of that process. This is what is considered as ‘the generation of flow’ (Melton 2005).

Organizations can benefit from lean thinking in several ways. Melton mentions that for non-process industries, benefits include, among others, reduced lead times for customers, reduced inventories for manufacturers, less process waste, and more robust processes leading to less errors and less rework (Melton 2005). Moreover, it may lead to financial savings because of decreased operating costs and potential capital avoidance (Melton 2005). More importantly with regard to information-based development, it leads to an increased understanding of processes (and of the supply chain as a whole) and of one’s customers, which potentially improves the organizational knowledge base (see chapter 5.2) and knowledge management activities (Melton 2005). By observing processes and subsequently identifying their value and waste, knowledge is obtained regarding these processes. Also, it is important to involve the people who run these processes daily and to unlock their knowledge (Melton 2005). Formally capturing this knowledge of processes is fundamental to the implementation of lean (Melton 2005). This knowledge can be captured and managed by IT systems or shared between people to increase its reach. More information about knowledge and knowledge management is presented in the following chapters.

Thirdly, the agile mindset is a mindset that is “rapid, iterative, easily adapted, and focused on quality through continuous improvement” (Schneider 2017). The term ‘agile’ stems from *agility* as a concept in manufacturing. Yusuf et al. define agility as “the successful exploration of competitive bases (speed, flexibility, innovation proactivity, quality and profitability) through the integration of reconfigurable resources and best practices in a knowledge-rich environment to provide customer-driven products and services in a fast-changing market environment” (Yusuf, Sarhadi et al. 1999). Agile manages and optimizes software delivery by focusing on creating software solutions that adapt to the changing needs of the user (Schneider 2017). To achieve this, a well-trained, motivated and knowledge-rich workforce is required that possesses the right set of skills, expertise, and knowledge (Yusuf, Sarhadi et al. 1999). Agile manufacturing is mutually compatible with lean manufacturing (Yusuf, Sarhadi et al. 1999, Schneider 2017). As mentioned by Schneider, the differences between the lean and agile mindset mostly come down to what they are applied to. He implies that both lean and agile are driven by change; both mindsets embrace it and adapt to it, regardless of the timing of which it occurs. Both mindsets focus on people (instead of processes) and quality, encouraging autonomy and collaboration between organizational members and improving efficiency. In addition, both mindsets produce value in an iterative way, seek to eliminate wasted effort, and focus on continuous improvement through reflection and learning. However, lean and agile are not interchangeable; agile focuses on optimizing software delivery, while lean focuses on optimizing "systems of work" that produce value for the customer (Schneider 2017). As Schneider explains "software delivery is one activity (among myriad other activities) that organizations do to produce value for their customers" (Schneider 2017). In addition, lean strives to achieve a continuous flow of value, while with agile the work is done in time-based iterations. Moreover, lean practice is about consistently producing the same output, while software in agile lends itself to continuous change.

As mentioned, an organization should not choose one mindset over the other, but it should rather combine all three mindsets to achieve the right outcome (Schneider 2017). Grossman-Kahn and Rosensweig (Grossman-Kahn and Rosensweig 2012) have created a model called 'The Discovery by Design Model for Innovation' that combines all three mindsets. See figure 16. The phases of design thinking as explained earlier in this paragraph (see also figure 12 on p.17) can be derived from this figure. Design thinking is followed by lean thinking which is represented by a cycle of learning by doing (described by the terms 'build' – 'measure' – 'learn'). Agile manufacturing is depicted as an iterative cycle that helps to create the right outcome within the cycle of learning by doing. By combining the three mindsets, the strengths of each mindset are used to achieve the right outcome. The combination of design thinking and lean thinking identifies opportunities and creates solutions through exploration, experimentation, and learning by doing. The combination of design thinking and agile manufacturing creates flexible solutions through software. Lean thinking and agile manufacturing reinforce each other: lean thinking provides the framework for learning by doing, while agile manufacturing enables learning by doing by providing the flexibility to respond to change (Schneider 2017).

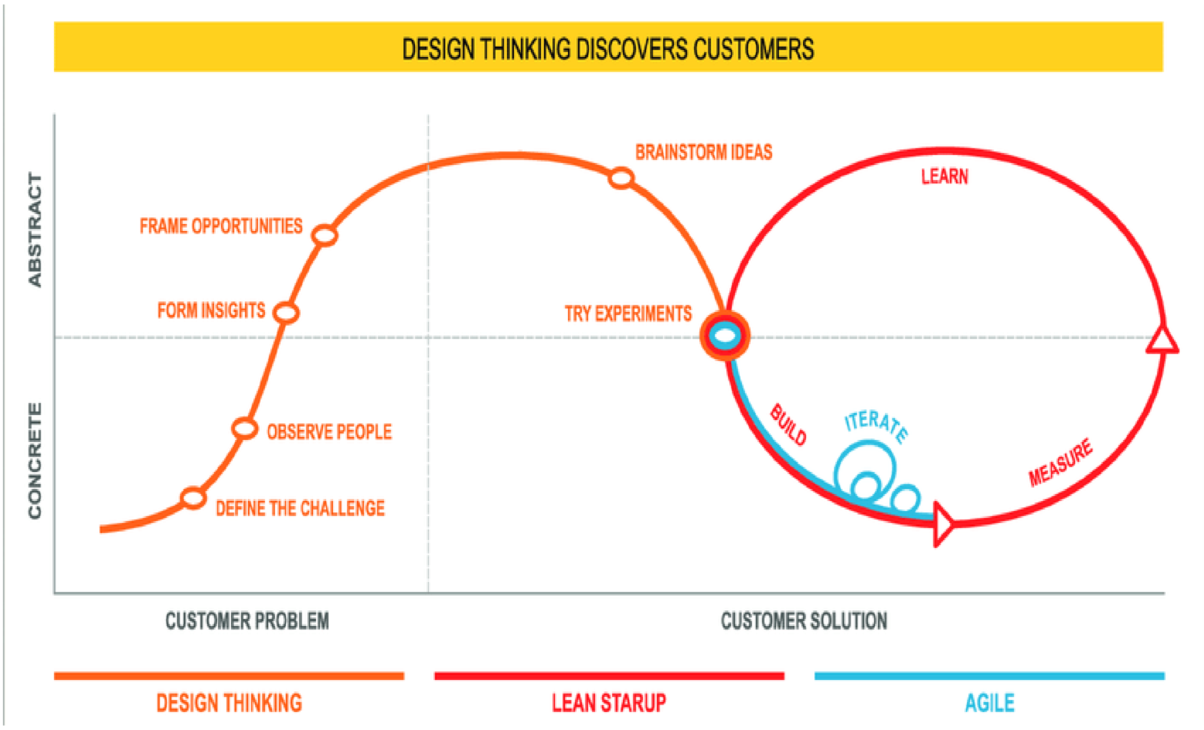


Figure 16: 'The Discovery by Design Model for Innovation' by Grossman-Kahn and Rosensweig (Grossman-Kahn and Rosensweig 2012)

Chapter 2.3: Decision-Making

Chapter 2.3.1: Types of Decision-Making

Decision-making is a central activity throughout a product's development trajectory, and even broader, throughout a product's life cycle. Decisions are made on a daily basis at both the lower and higher levels of an organization. Decision-making can be defined as "the selection of one option from a set of two or more options" (Klein, Calderwood et al. 2010). From an information perspective, it can be viewed as creating a change in information content (De Lange 2018). This statement is elaborated upon in chapter 2.3.3. Decision-making is a combination of conscious and deliberate reasoning, and intuition gained through experience (see chapter 3.5.1) (see e.g. (Klein, Calderwood et al. 2010, Salas, Rosen et al. 2010)). To make high-quality decisions, knowledge is of critical importance (Sharda, Frankwick et al. 1999). Knowledge is gained through experience or obtained by actively searching for it (Kakabadse, Kouzmin et al. 2001). Especially in group decision-making, sharing and obtaining information is essential to generate and evaluate alternatives (Sharda, Frankwick et al. 1999).

Decision-making can be categorized into two types of decisions: programmed decisions, which are often most efficiently made by computers through deterministic models, and non-programmed decisions, which are best executed by people. Programmed decisions deal with structured, routine problems that have a certain outcome or from which the risk can be calculated. Because the information necessary to make this type of decision is readily available and only requires objective judgement from the decision-maker, this type of decision can be effectively executed at the lower and middle levels of an organization. Most decisions of this type can be executed by using policies, standards, and rules. In contrast, non-programmed decisions deal with unstructured, unusual problems that have an uncertain outcome because of their non-repetitive nature. Because the information necessary to make such decisions is ambiguous and/or incomplete, this type of decision is often executed by the top-level of an organization. This type of decision thus relies on knowledge obtained through experience, judgement, and creativity. See table 5.

	PROGRAMMED DECISIONS	**NON-PROGRAMMED DECISIONS**
NATURE OF PROBLEM	Structured	Unstructured
FREQUENCY	Repetitive, routine	Non-repetitive, unusual
INFORMATION	Readily available	Ambiguous or incomplete
JUDGEMENT	Objective	Subjective
METHOD OF SOLVING	Policies/standards/rules	Experience/judgement/creativity
PROBABILITY OF OUTCOME	Certain/risk	Uncertain
MANAGERIAL LEVEL	Middle/lower level	Top-level
TYPES	Organizational/operational/ research/opportunity	Personal/strategic/crisis/intuitive/ problem-solving

Table 5: Programmed vs non-programmed decisions

Decisions can be made under one of three conditions as depicted in figure 17. The first decision-making environment regards decisions that are made under the condition of certainty. In this type of decision-making environment, a decision-maker knows with reasonable certainty what the outcome of a decision is going to be. In case of decisions made under certainty, the decision-maker knows what conditions are associated with each alternative and thus only one single outcome is likely in a certain situation (Li and Madanu 2009). Decisions made under certainty are exceptional, although routine type of decisions can come close. This is also why precisely following the activities that are prescribed by process-based models is advised against. Process-based models assume that products are developed under the condition of certainty. However, decisions made during product development, and especially during the execution of innovative projects, are never certain, because they often regard non-programmed decisions or *wicked problems* (see chapter 2.2.2). Furthermore, this method of development not only assumes that following the prescribed process results in better product designs, more importantly, it may give the impression that product development is a predetermined, unquestionable process that is executed under the condition of certainty. As explained, this is almost never the case.

The second decision-making environment regards decisions that are made under risk. In this type of decision-making environment, a decision-maker knows the range of possible outcomes and knows the probability of each outcome (Li and Madanu 2009). It can be difficult to distinguish risk from uncertainty; risk is an implication of uncertainty, contrasting to the assumption that risk is uncertainty (Perminova, Gustafsson et al. 2008). In addition, risk implies certain knowledge and thus enables calculability and controllability, in contrast to uncertainty that implies that there is no certainty at all (Perminova, Gustafsson et al. 2008). In conditions of risk and uncertainty, techniques such as risk analysis, decision trees, and preference theory may improve the quality of decision-making. Perminova et al. provide three different perspectives on risk, from an economics, psychology, and project management viewpoint. They define risk from an economics viewpoint as "events subject to known or knowable probability distribution", from a psychology perspective as "the fact that the decision is made under conditions of known probabilities", and from a project management view as "an uncertain event or condition that, if it occurs, has a positive or negative effect on at least one project objective, such as time, cost, scope, or quality" (Perminova, Gustafsson et al. 2008). These three definitions provide a clear difference between environments of risk and environments of uncertainty.

The third decision-making environment regards decisions that are made under the condition of uncertainty. In this type of decision-making environment, a decision-maker does not know the range of possible outcomes and does not know the probabilities and/or consequences of these outcomes (Li and Madanu 2009). Even if a decision-maker wanted to, it is impossible to calculate the risk or probability of an outcome (Perminova, Gustafsson et al. 2008). The outcome of a decision is often uncertain because of external factors such as product demand, behavior of competitors, and other factors that are uncontrollable. As mentioned earlier, most decisions that are made in product development environments (and especially those environments that deal with the creation and execution of innovative products and projects) are made under the condition of uncertainty, because these external factors cannot be managed.

Figure 17 describes the conditions for a decision to be certain, risky, and uncertain. Naturally, with each decision-making environment the level of ambiguity and the chance of making a bad decision becomes higher as the level of certainty decreases.

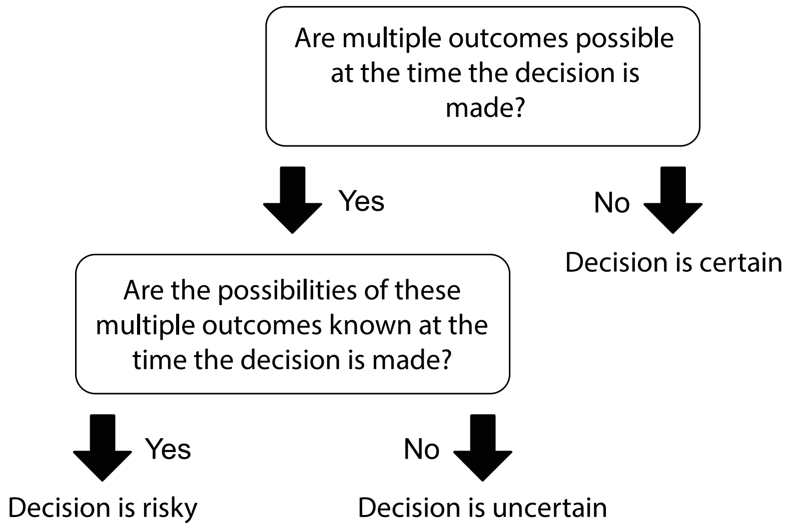


Figure 17: Conditions of certainty, risk, and uncertainty in decision-making environments[5]

[5] University of Washington, 'Decision Making in Organizations', Retrieved from http://courses.washington.edu/inde495/lecc.htm

Chapter 2.3.2: Steps in the Decision-Making Process

In literature, multiple variations of the decision-making process can be found, mostly varying between five and eight process steps. Generally, they describe the same activities, though in some cases certain steps are merged. A concise description of the decision-making process is given in figure 18. This process can be used for both individual decision-making and group decision-making.

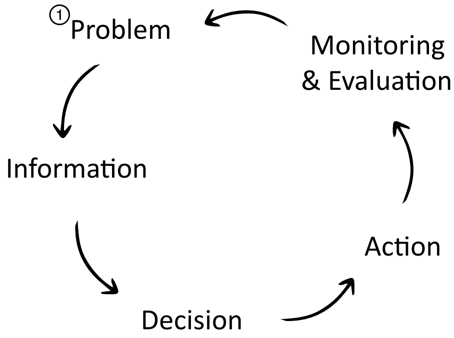


Figure 18: Steps in the decision-making process

The decision-making process starts with identifying and defining the problem or opportunity at hand and recognizing that there is a decision to be made. Clearly describing the problem and the decision that must be made avoids misinterpretation during the process of decision-making and prevents an outcome that is not desirable or beneficial to the development of a product. Then, relevant information and knowledge must be collected to facilitate the decision-making process. As mentioned in chapter 2.3.1, sharing of information and knowledge is essential in decision-making. In this step, an individual or group must identify one's/their available resources and identify one's/their constraints. Resources include people, money, time, materials, and equipment, but also information, knowledge and expertise. By identifying available and required resources, one can indicate potential constraints and limitations regarding these resources. When the necessary resources are identified and acquired, possible solutions and alternatives must be generated, identified, and evaluated. Alternatives can be weighed against each other to come up with the best decision. Then, a decision must be made among alternatives. Depending on the condition of the decision-making environment (certainty, risk, or uncertainty, see chapter 2.3.1) and the accompanying level of ambiguity, overseeing the consequences of a decision can be relatively easy to very difficult. Means such as research and analysis, experimentation, and experience can help in decision-making. After a decision is made among alternatives, action must be undertaken to implement the decision. Such action can include, for instance, updating people regarding the decision that is made, to updating a product to implement the decision. Lastly, the consequences of a decision must be monitored and reviewed. By analyzing the consequences of a decision, new knowledge can be obtained that can be helpful in future decision-making processes.

As can be seen from figure 18, the act of decision-making is only a small part of the whole decision-making process. People often focus their attention on this part of the decision-making process, although from an information perspective, their attention should be focused on obtaining relevant information and knowledge in order to make high-quality decisions. Sharda et al. support this claim by stating that "the quality of a decision or a solution to a problem is dependent on the quality of the accompanying knowledge" (Sharda, Frankwick et al. 1999). However, decision-making remains a difficult task as the outcome of a decision can never be predicted with 100% certainty; thus, high-quality information and knowledge must be sought after to enhance this process.

Chapter 2.3.3: The Importance of Decision-Making in Information-Centered PD

Decision-making is a central activity throughout a product development trajectory and life cycle. Its importance can be viewed from multiple perspectives. This paragraph shortly explains the importance of decision-making from a business perspective and from an information perspective in general.

Decision-making as viewed from a business perspective can be important to an organization in several ways. Above all, decision-making is important to achieve organizational objectives. Through the decision-making process, the best alternative is identified that can achieve a certain objective. In this way it also supports business growth and facilitates innovation. In addition, decision-making increases efficiency by quickly solving problems and challenges and by motivating employees to include their own decisions. In contrast to decision-making viewed from a business perspective, decision-making viewed from an information perspective does not focus directly on organizational objectives. From an information perspective, decision-making focuses on creating information and knowledge. In information-centered product development, information is regarded as the main driving force. De Lange (De Lange 2018) clearly explains how decision-making and the information content in a product development cycle are interrelated. He explains that when the act of designing itself is viewed as the creation of information, decision-making is the main (value-adding) activity that establishes and transforms this information. In this way, every decision that is made transforms the current information content and can enrich an organization's knowledge base (see chapter 5.2) by monitoring and evaluating the outcome of a decision. See figure 19. This (transformed) information content can in turn serve as information input for new product development activities and decision-making processes.

Because decision-making enriches the organizational knowledge base, it can be very useful to an organization. Not only does decision-making achieve common goals such as business growth and innovation, it also creates new information and knowledge within an organization. Information is a very important resource within any organization, as it is essential for effective operation and decision-making (Kaye 1995). Merely processing information is not enough; organizations must also create it (Nonaka 1988). Thus, decision-making is a very important source of information and knowledge within organizations.

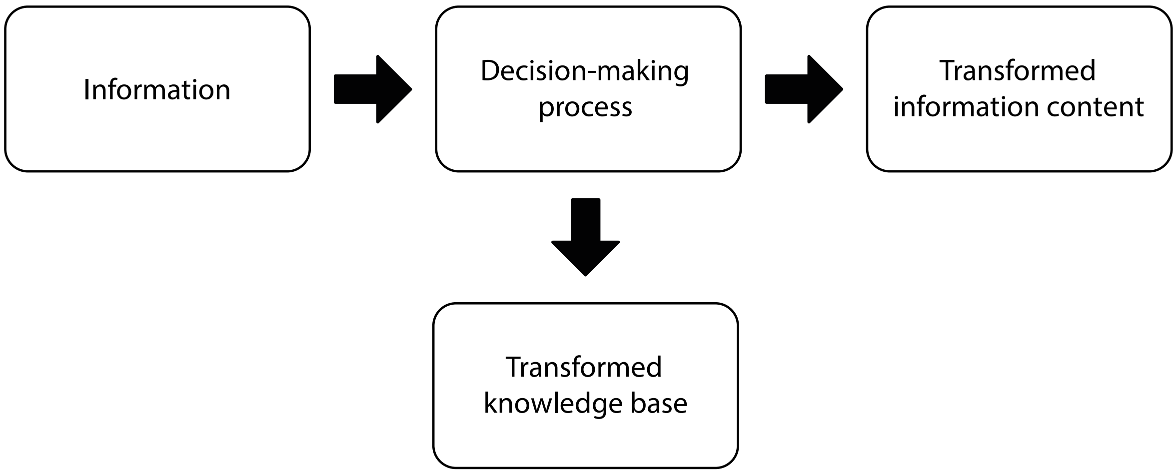


Figure 19: Information transformation process

Chapter 2.4: Information Management

In order to make high-quality decisions and enhance problem solving, relevant information must be obtained to gain knowledge. To obtain relevant information in an efficient and effective way, information needs to be managed. By managing information, it can be made available to organizational members and can be reused by those people that are in need of information. Thus, the purpose of information management is to ensure that the right information is available in the right place/to the right people at the right time, in the right format and quantity. It is the infrastructure used to capture, store, and reuse information. This paragraph explains how information management can be useful to an organization and gives a concise description of the process of information management based on the information life cycle.

Chapter 2.4.1: Aims of Information Management

Information management can have several objectives within an organization. A few important aims that can be fulfilled through information management are explained now.

A first important aim of information management is to support product development activities. By managing and supplying information to the people in need of information, processes performed by these people can be executed more efficiently and effectively. To manage information assets and information resources within an organization, the concept of Information Resource Management (IRM) can be employed. Information resource management is defined by Schneymann as "the management (planning, organization, operations and control) of the resources (human and physical) concerned with the systems support (development, enhancement and maintenance) and the servicing (processing, transformation, distribution, storage and retrieval) of information (data, text, voice, image) for an enterprise" (Schneymann 1985). Thus, IRM is concerned with the management of information assets within an organization. Information management provides the foundation for knowledge management, as the information that is managed can help to create new knowledge; however, information management is not synonymous to knowledge management ((Teece 2000, Kakabadse, Kouzmin et al. 2001, Hawamdeh 2002)). See table 6. Information management focuses on collecting, managing, storing, and delivering information. In this way, it connects a range of resources such as data, information, technology, and information systems. Knowledge management, on the other hand, focuses on connecting people, as knowledge is mainly stored in heads rather than on hard disks.

	INFORMATION MANAGEMENT	KNOWLEDGE MANAGEMENT
TYPE OF INFORMATION/ KNOWLEDGE	Propositional (know that/what) Epistemic (know that and why)	Experiential (know of) Performative (know how)
CONVERSION	Data to information	Information to knowledge
PURPOSE	Connecting content	Connecting people
MANAGEMENT FOCUS	Documents and its access, security, delivery, and storage	People and their experiences
DRIVEN BY	Technology	People, processes, and management

Table 6: Differences between information management and knowledge management

A second important aim of information management is to support the process of decision-making. Ada and Ghaffarzadeh claim that information is of pivotal importance in decision-making (Ada and Ghaffarzadeh 2015). They state that “effective decision-making demands accurate, timely and relevant information” (Ada and Ghaffarzadeh 2015). Every decision is guided by information, as can be seen from figure 18 on p.25. Therefore, information management is necessary to make well-founded decisions. However, not all information that is managed by an information system is relevant information. Relevance depends on the context in which information is created and used and that applies to that information; context is also the factor that differentiates information from knowledge (see figure 23 on p.32). Thus, an information system must be able to make a distinction between collected information and usable, relevant information in order to accomplish efficient and effective operation within an organization. See figure 20.

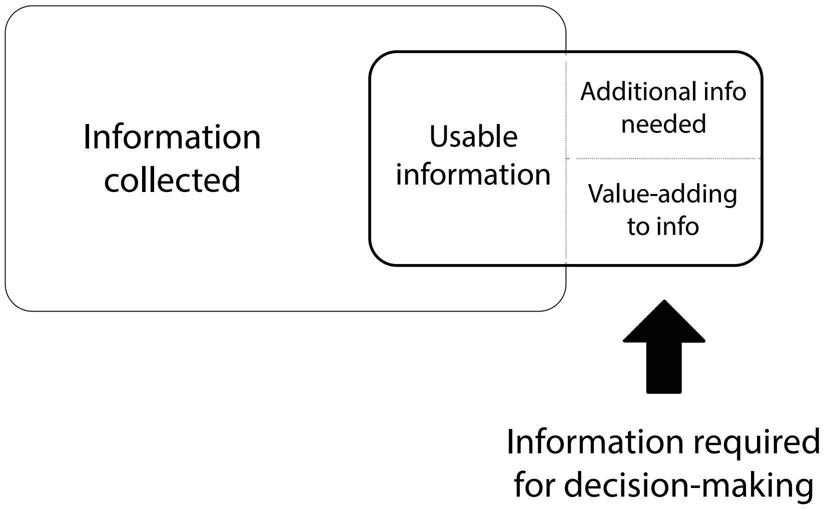


Figure 20: Information required for decision-making (Srinivas 2015)

A third important aim of information management is to provide process guidance and enable process improvement. As explained, information-based development focuses on the information content itself rather than on the processes needed to develop and realize a product. When the information content is used as the basis for product development, the processes can be arranged around the information content. In this way, the processes can be organized in a more flexible manner than just being a predefined sequel of activities. Now, the processes can be used to achieve a change in information content rather than just prescribing a way of working. Consequently, the processes are used by organizational members to achieve the desired transformation of information. As a result, the information content and its (required) evolvement guides the product’s development, and the processes are just tools to achieve a certain transformation of information.

Chapter 2.4.2: The Information Life Cycle

A short, general description of information management is given based on the information life cycle. The information life cycle can be divided into 4 components, which are the creation or capture of information, use of information, storage and retrieval of information, and information destruction or preservation. See figure 21.

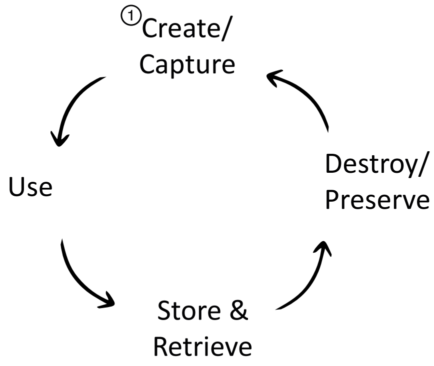


Figure 21: An information life cycle

The components of information management are fairly self-explanatory. In the first step, which deals with records from their point of origination, information is created by a member of an organization in the form of correspondence, forms, reports, drawings, etc., or it is received/captured from an external source. In the second step, information is shared with organizational members and used to make decisions, solve problems, document further actions, or serve other purposes. In the third step, information is filed, retrieved, and transferred. Attention must be paid to how information is filed (i.e. how it is arranged) in order to enable effective retrieval and reuse. The last step is concerned with the handling of information that is less frequently accessed or has met its assigned retention period[6]. Less frequently accessed records may be archived/relocated until they have met their assigned retention period and are being destroyed. By executing this step, the degrees of usability of the information can be separated.

Although the steps in information management are self-explanatory, the order in which they are presented is not. As mentioned in the goal of this thesis, a system is designed that provides the user with relevant information, instead of providing them with all available information. With the goal to store useful and accurate information instead of all possible information, the order of creating/ capturing information, using information, and then storing information ('capture-use-store') is used as can be seen from figure 21. By using this order of actions, information is created, used, and then stored and managed. In literature the order of 'capture-store-use' is also described, however this approach stores information before it is used. Although the objective of this approach is clear, namely to store information in order to disseminate it, this order of events may store more information than necessary. As mentioned, too much information can cause (the feeling of) information overload and this must always be avoided. Therefore, attention must be paid to the information that is stored in the system to avoid an overload of information with low degrees of usability.

[6] The retention period of a record identifies the duration of time for which the information should be maintained or "retained".

Chapter 2.5: An Information-Based Development Model

By combining the three categories of activities that are explained in this chapter, an information-based development model can be drafted. See figure 22.

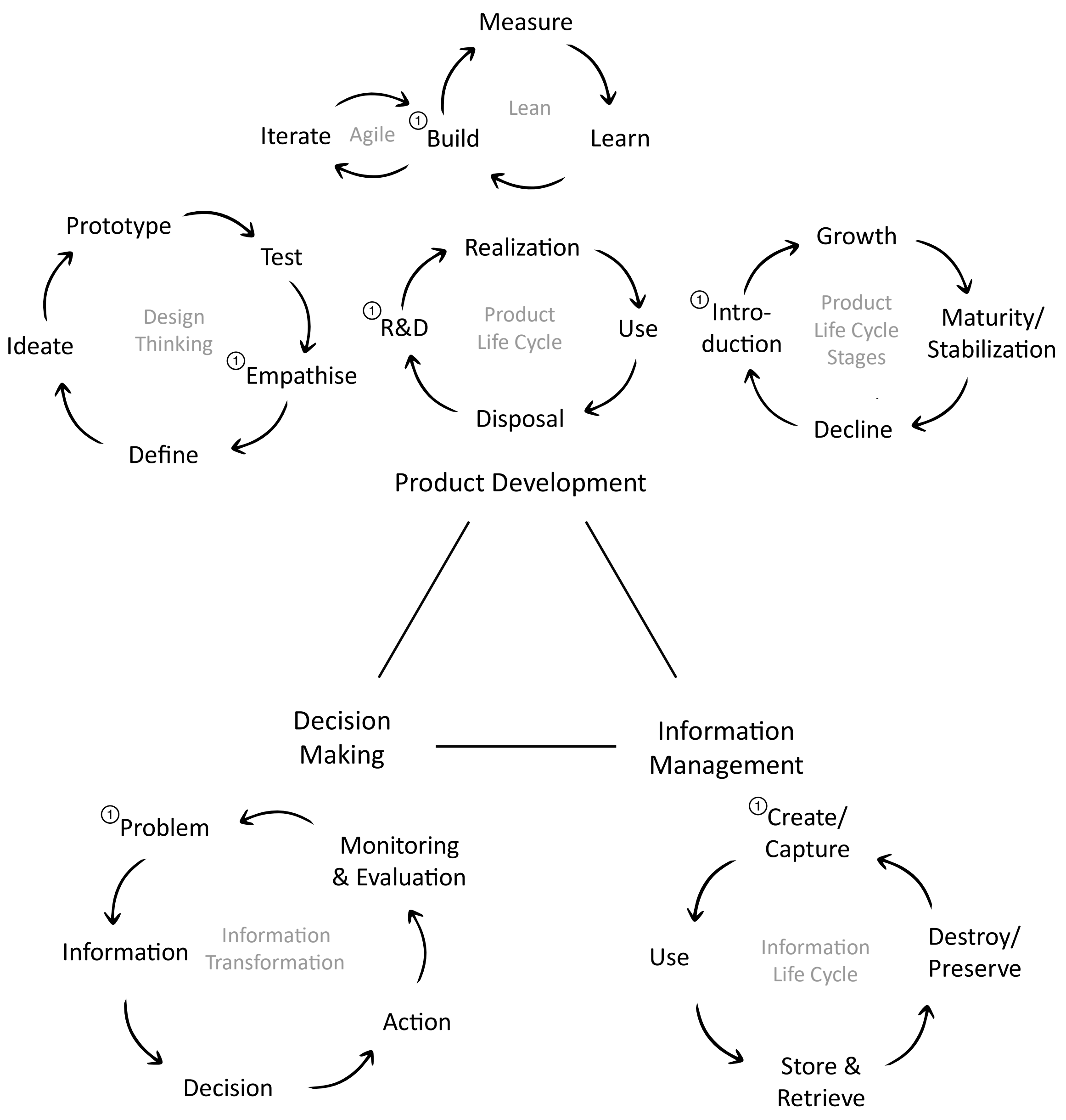


Figure 22: An information-based development model

This model helps to visualize the activities that are important in information-based product development. Activities regarding the execution of product development processes are centered around the product life cycle and incorporate the three mindsets of product development (design thinking, lean, and agile). Decision-making is depicted as an independent activity that enables the transformation of information. Because the process of decision-making is a central activity throughout a product's life cycle, it is separated from the processes that are used in product development. The same applies to information management activities; because information management is fundamental in information-based management, it is depicted as independent activity.

Chapter 2.6: Conclusion

This chapter has described three categories of activities that contribute to information-based product development. It has been argued that product development should focus on three independent but connected components: firstly, the processes that are involved in product development; secondly, decision making, i.e. the transformation of information that originates from product development; and thirdly, information management, i.e. the reuse of information created in and captured from past, current and future product development activities. The interplay of these three components forms the basis for information-based product development.

The division of product development processes, decision-making, and information management is not a definitive or final division. Another division of product development components could have been made when, for instance, other literature would have been used. Other divisions have been considered, however, after reviewing several options, the division used in this chapter is chosen based on personal beliefs and judgement. Moreover, this division relates to the context of information-based product development and might be altered to fit other contexts.

Chapter 3: Knowledge Creation Through Artifacts

Chapter 3.1: Introduction

The previous chapter describes several product development activities that should take place in information-centered product development. Decision-making is a central activity in product development (and throughout a product's life cycle in general) and requires relevant and high-quality information and knowledge (Sharda, Frankwick et al. 1999). From the activities mentioned in chapter 2, a lot of information and knowledge arises that can aid in decision-making and problem solving. To determine how knowledge is created and how it can be used to enhance decision-making and problem solving, it is necessary to understand the term 'knowledge'. However, it is hard to define the term 'knowledge' because it has many dimensions; therefore, several definitions and theories of knowledge exist. In literature, multiple definitions can be found that describe the meaning of the word knowledge, slightly varying in focus and perspective. To demonstrate this difference in approach, three definitions are provided that each highlight an important aspect of knowledge:

"Knowledge is the context that enables the analysis and adaptation of a situation, based on the interpretation of information" (Lutters 2001)

[Knowledge is] "information given meaning and integrated with other contents of understanding" (Bates 2005)

[Knowledge is] "facts, information, and skills acquired through experience or education" (Simpson, Weiner et al. 1989)

The first definition focuses on interpretation of information. To interpret information and potentially become knowledge, a context is needed; information without context is no more than data. Knowledge serves as this context that gives meaning to information. The second definition also highlights meaning but focuses on understanding. Information can have meaning, but one needs context to understand its meaning. The last definition focuses on how knowledge can be obtained: knowledge is a consequence of education and experience. To further clarify the relationship between information and knowledge, the often used DIKW hierarchy (figure 23) is presented that situates knowledge among data, information, and wisdom.

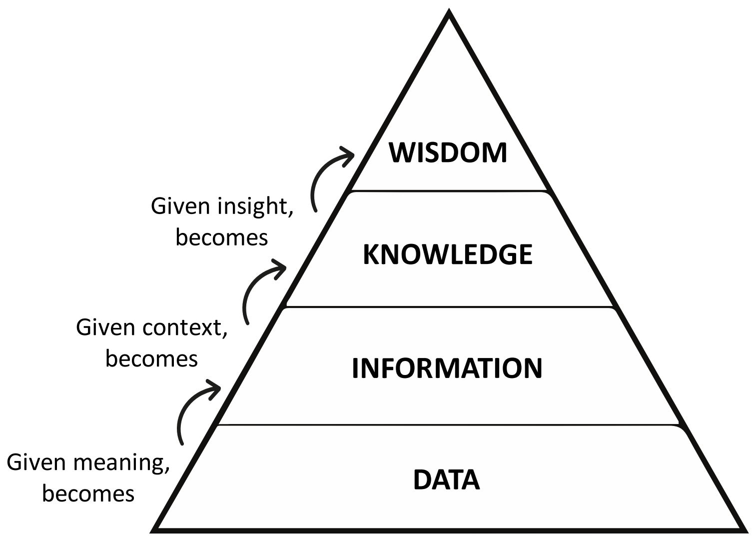


Figure 23: DIKW hierarchy – Based on (Gajzler 2016)

The concepts of information and knowledge are often mixed up and tend to be used interchangeably in literature and practice (Kakabadse, Kouzmin et al. 2001). As can be seen from the DIKW hierarchy in figure 23, knowledge can be viewed as information in context. Knowledge is often perceived as being explicit, tangible and measurable. This type of knowledge is called 'explicit' knowledge and is often used synonymously with the term 'information'.[7] Explicit knowledge is formal and systematic and is obtained by actively searching for it through, for example, education, repositories and work context (Kakabadse, Kouzmin et al. 2001); it can be expressed in words and numbers and shared in the form of data, documents, books, manuals, specifications, etc. (Nonaka 1991, Nonaka and Konno 1998). Because this type of knowledge is explicitly available, it can be easily communicated and shared. However, there is also a very important tacit dimension to knowledge, firstly described by Polanyi (Polanyi 1958) and later popularized by Nonaka and his companions (Nonaka 1991, Nonaka and Takeuchi 1995, Nonaka and Konno 1998). This type of knowledge is called 'tacit' knowledge. Nonaka describes tacit knowledge as knowledge that is highly personal and deeply rooted in a person's actions and experiences. This type of knowledge is acquired through experience and is hard to formalize, and therefore difficult to communicate and share. In literature, the term tacit knowledge has been attributed to knowledge that has not been made explicit as well as to knowledge that cannot be made explicit (e.g.(Nonaka 1991, Zander and Zander 1993)). For tacit knowledge that has not been articulated but that could be articulated, Nonaka uses the term 'expressible' tacit knowledge; for knowledge that cannot be articulated, he uses the term 'inexpressible' tacit knowledge (Nonaka 1991). For this research, tacit knowledge is interpreted as knowledge that has not been made explicit, as well as knowledge that cannot be made explicit. Thus, the following definition of tacit knowledge is adopted:

Everything that is not explicit(ly documented) knowledge, is tacit knowledge.

Naturally, both types of knowledge are created during the development of a product. This knowledge is captured in "products" that arise from the context of product development. To elaborate on these products that are created during product development, Simon's concept of "artifact" is used (Simon 1996). Simon considers artifacts to be *"artificial things [...] synthesized (though not always or usually with full forethought) by human beings"* (Simon 1996). What is interesting about this definition is that an artifact does not have to be created with full forethought; this means that it can be created by any human being and not just by designers (Lee, Thomas et al. 2014). Moreover, it also means that an artifact does not need to be anything physical; theories and ideas also count as artifacts (Lee, Thomas et al. 2014). Describing these products in the form of artifacts enables them to be created without full forethought and as something tangible as well as intangible. This means that a product of a development trajectory can be something as physical as a paper document, but also as abstract as the relationships that are created between organizational members. To make these "products" more comprehensible, a division is made between social artifacts, information artifacts, and technology artifacts. See figure 24. In a very general sense, product development creates three things: the end-product itself and tools to come to this end-product (i.e. technology artifacts), information instantiations necessary to create the product (i.e. information artifacts), and social networks and relationships necessary to develop the product (i.e. social artifacts). Knowledge can be derived from these three types of artifacts, because they embed knowledge that is used to create them. For example, a relationship between two organizational members embeds knowledge about personal interests and experiences, and a paper document embeds knowledge about certain topics. Being aware of the artifacts that are created during product development, and the knowledge that can be

[7] The terms 'information' and 'explicit knowledge' are used interchangeably in this thesis. This is because explicit knowledge is regarded as searchable and easy to find information in context.

derived from them, can create new knowledge among individuals. Which knowledge can be derived from social artifacts, information artifacts, and technology artifacts, and how (having knowledge of) these artifacts can be useful to an organization, is explained in the following paragraphs.

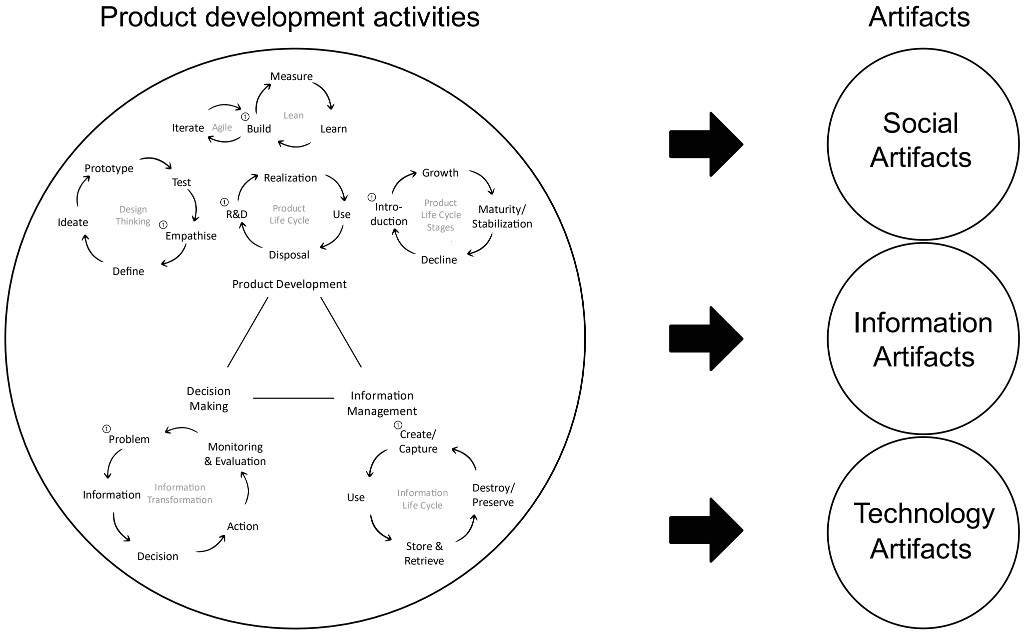


Figure 24: Artifacts i.e. “products” that are naturally created through product development

Chapter 3.2: Social Artifacts

In organizations, many organizational structures, systems, hierarchies, roles and other social relations can be found. To describe these networks and their relations, the term 'social artifact' created by Lee et al. (Lee, Thomas et al. 2014) is used. Lee et al. define a social artifact as *"an artifact that consists of, or incorporates, relationships or interactions between or among individuals through which an individual attempts to solve one of his/her problems, achieve one of his/her goals, or serve one of his/her purposes"* (Lee, Thomas et al. 2014). They speak of 'social' artifacts as relationships and interactions involve more than just one person. Hence, social artifacts refer to knowledge about the social; organizational structures, organizational cultures, roles, and laws are examples of social artifacts (Lee, Thomas et al. 2014). This knowledge can be explicitly documented (i.e. being explicit knowledge) as well as residing in people's minds (i.e. being tacit knowledge).

Social artifacts can be of use to an individual in general or decision-maker in particular by providing knowledge about social relations and interactions. As a consequence, social artifacts can enhance the efficiency and effectiveness of organizational processes. During the product development cycle, many people with different perspectives and interests are involved in many different processes. These people all have their own experiences and accompanying knowledge obtained through these experiences. This knowledge is of pivotal importance in making high-quality decisions as it is regarded as the most important element in the decision-making process (Sharda, Frankwick et al. 1999). To get access to this knowledge, people must either share their personal knowledge with other people, or individuals need to have an idea of which individual possesses which knowledge to come close to the source of the knowledge one is seeking. This is where social artifacts can be useful: by knowing structures, hierarchies, roles, job positions, etc. and accompanying knowledge of people that work in an organization (or any other relevant subdivision/subsystem such as a project group), processes can become more efficient and effective because one knows or at least has an idea of where or whom to go for to obtain specific knowledge. Especially in the research and development phase of a product where many important decisions are made and different perspectives are needed to come up with the best product, social artifacts can make these processes run more smoothly. The research and development phase of a product is just an example, but this holds for all phases involving people. In addition, social artifacts can enable and stimulate the sharing of knowledge and experiences among individuals in general. It is important to share knowledge, as shared knowledge is more likely to be used than personal knowledge (Cruz, Boster et al. 1997). Moreover, decisions that are based on shared knowledge are usually of higher quality than decisions based on personal knowledge (Cruz, Boster et al. 1997). Social artifacts can facilitate knowledge sharing: when an individual is aware of whom to go for to obtain the knowledge he/she is searching for, explicit knowledge can be transferred directly from this person (the source of knowledge) to the person in need of knowledge. The transfer of tacit knowledge requires a different process, which is explained in chapter 4.

Chapter 3.3: Technology Artifacts

Product development often starts when there is a problem that can or needs to be solved or an opportunity that can be exploited. Thus, products are designed and created with a specific goal or purpose in mind. Moreover, they are created to have a certain function. These types of products are called technical, technological or technology artifacts. In literature several definitions can be found for this type of artifact, which are very different from one another. Firstly, Frederik et al. (Frederik, Sonneveld et al. 2011) define technical artifacts as "human made objects that have a certain function, and have been made because of that". This definition is in agreement with Simon's definition of artifact: an object that is created by human beings (Simon 1996). Furthermore, they state that "to be a technical artifact, the entity needs to have a function, but also to be a physical object". This part of their definition is conflicting with Simon's definition of artifact, which does not limit artifacts to be something physical. Therefore, this definition of technical artifact excludes any type of virtual tool that might be created to solve a problem. Secondly, Verbeek and Vermaas (Verbeek and Vermaas 2012) define technological artifacts as "clear-cut manifestations of technology". They add that technology artifacts are "material objects made by engineers for practical uses". This definition is coherent to the used definition of artifact in the way that the artifact must be human-made and thus non-natural. However, similarly to Frederik et al.'s definition of technical artifact, it excludes all non-physical tools and, even more noteworthy, any other material objects that are not created by engineers. Therefore, this definition is naturally very limiting. Lastly, Lee et al. define a technology artifact as *"a human-created tool whose raison d'être is to be used to solve a problem, achieve a goal, or serve a purpose that is human-defined, human-perceived or human-felt"* (Lee, Thomas et al. 2014). This definition is the most including one that is found; in their research the authors state that technology artifacts can be electronic as well as non-electronic, do not need to be about information per se, and do not need to be physical. Although the definitions created by Frederik et al. and Lee et al. could both have been used for this research (as this research focuses on the development of physical products), the definition created by Lee et al. is preferred over the other definitions because this is unrestrictive and overall fits Simon's definition in a better way.

Technology artifacts can provide knowledge that is embedded in the artifact itself. For example, looking at the design of a chair or ball, possible interactions and its potential goal or purpose can be derived from the artifact without having information about the exact goal or purpose of the artifact. This is called *affordance.* The concept of affordance is invented by Gibson to define the relationship between an actor and an object, or between an actor and their environment (Gibson 1977). In relation to physical objects, affordances can be defined as "an object's properties that show the possible actions users can take with it, thereby suggesting *how* they may interact with that object".[8] Because a chair has a flat surface, it affords sitting on; because a ball is relatively small and round, it affords throwing. However, an actor may throw the chair and sit on the ball because this is objectively possible. Thus, affordance refers to all possible actions an actor can perform with an object or environment. In contrast, an object's *perceived* affordance is based on an actor's past experiences. Based on experience, a chair only affords sitting on. Thus, technology artifacts can provide tacit and explicit knowledge about the created tool itself, as it is embedded in, for instance, the design/appearance of the tool itself. Moreover, technology artifacts can embed knowledge of who might have been involved in its development. Creating a chair at least requires a designer and an engineer, or an expert who specializes in creating chairs. With this information, and the information of who has been involved in its development, one can get an idea of whom to go for to obtain specific knowledge one is searching for.

[8] Interaction Design Foundation, Retrieved from https://www.interaction-design.org/literature/topics/affordances

Chapter 3.4: Information Artifacts

In order to develop and create new products, lots of information is created and disseminated to people in need of information and knowledge for e.g. decision-making purposes and problem-solving activities. As explained, information-based development revolves around this information. This information can be spread through documents, standards, manuals, e-mails, and other instruments that instantiate information. Lee et al. describe these instantiations of information as 'information artifacts' (Lee, Thomas et al. 2014). They define an information artifact as *"an instantiation of information, where the information occurs through a human act either directly (as could happen through a person's verbal or written statement of a fact) or indirectly (as could happen through a person's running of a computer program to produce a quarterly report)"* (Lee, Thomas et al. 2014). This means that an instantiation of information is triggered by a human action; this action might be as simple as sending an e-mail containing meeting minutes, or as difficult as decision-making and the change it creates in information content (see chapter 2.3.3). In addition, the provided definition suggests that an information artifact can be physical as well as non-physical; a statement written on paper is as much an information artifact as a document stored on a computer. Based on the definition created by Lee et al., this thesis defines information artifacts as *instantiations of explicit knowledge created through human action.*

Organizational members can instantiate information for several reasons. The first and possibly most important reason to instantiate information is to disseminate and manage it throughout an organization. When information is instantiated, it is made explicit and can then easily be made available to other people. See figure 25. From this information artifact one can obtain explicit knowledge (i.e. information in context) but one can also derive tacit knowledge from this information artifact; when explicit knowledge is interpreted or used to obtain new knowledge, this knowledge is tacit until it is made explicit in some way. Secondly, instantiating information gives context to information. Through information artifacts, information is put into context. This context is necessary to obtain knowledge from information (see figure 23 on p.32). Without this context, information would just be useful data. Thirdly, information can be instantiated to reduce lack of order (Lee, Thomas et al. 2014). When tacit knowledge is instantiated and becomes explicit knowledge, it is crystallized and can then, when disseminated, prevent disorder. However, dealing with too many information artifacts can have the opposite effect: too much information, or information overload, can pose a threat to aspects of knowledge quality such as relevance (Sharda, Frankwick et al. 1999). Thus, this must be avoided by all means. Lastly, information artifacts can serve as an aid in decision-making processes. Knowledge is generally considered to be the most important element in decision-making and problem solving (Sharda, Frankwick et al. 1999). Sharda et al. state that "the quality of a decision or a solution to a problem is dependent on the quality of the accompanying knowledge". Knowledge quality is determined by several factors including accuracy, consistency and certainty, as well as clarity, meaning, relevance and importance (Holsapple and Whinston 1996). When an information artifact provides high quality knowledge, it can enhance decision-making and problem-solving processes and reduce the probability of a bad outcome.

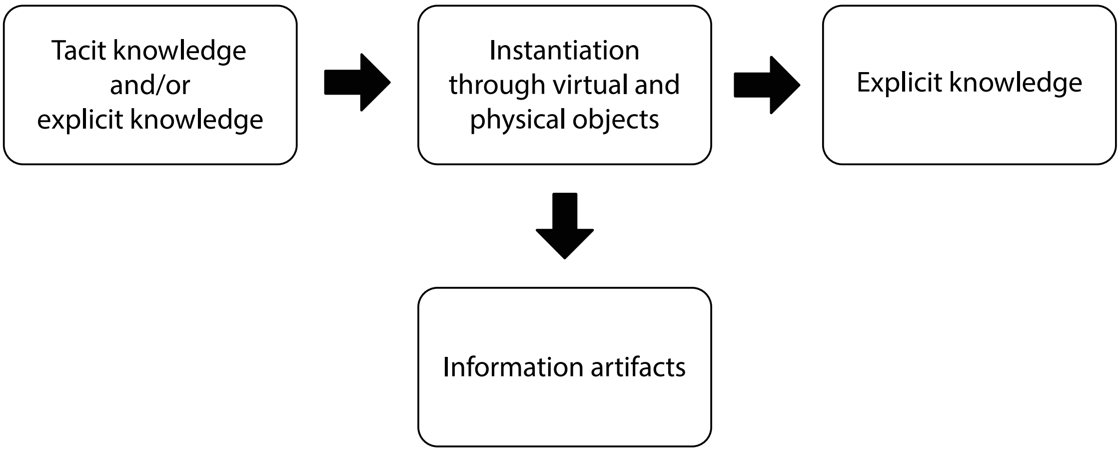


Figure 25: Information instantiation process

Chapter 3.5: Other Knowledge Sources

Artifacts are, by definition, human-made 'things' from which knowledge can be derived. This 'thing' can be anything from a relationship or interaction (social artifact) to a document or e-mail (information artifact) to a tool that serves a certain function (technology artifact). In contrast to artifacts that are human-made, there are also natural, non-human-made sources from which knowledge can be obtained. As explained, this knowledge is important to make decisions and solve problems. Some examples are given below.

Chapter 3.5.1: Intuition

When we make decisions, either consciously or unconsciously, we often rely on past experiences and tacit knowledge that is acquired through these experiences. One of these forms of tacit knowledge is intuition. Intuition is generally described as "the ability to understand things without using logic" and it is therefore important in innovation and decision-making (Spacey 2016). The human brain constantly compares incoming sensory information and current experiences to accumulated knowledge and past experiences to determine an appropriate course of action (Van Mulukom 2018). This is called 'pattern recognition' or 'pattern matching' (Salas, Rosen et al. 2010). See figure 26. This comparing of current experiences to past experiences is an automatic and subconscious process. Intuitions occur when the brain has formed a significant match or mismatch between past and current experiences, but this has not yet reached one's conscious awareness (Van Mulukom 2018). A well-known example of intuition is gut-feeling.

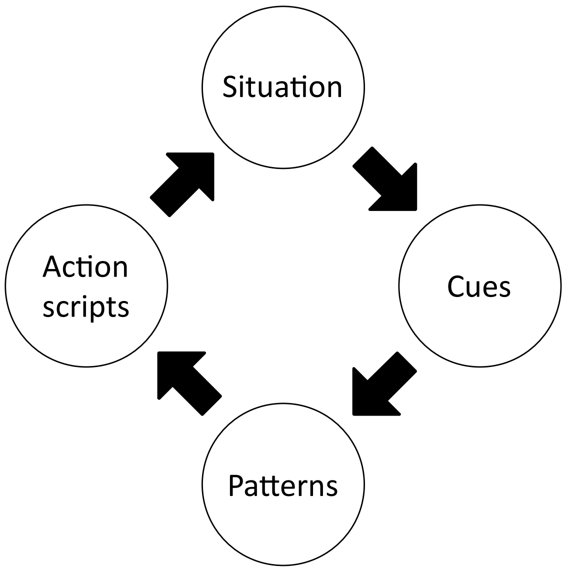


Figure 26: Pattern Recognition Process Behind Intuitive Decision-Making (Klein 2007)

Intuition is acquired through long experience and learning (see e.g. (J. Isenberg 1984, Simon 1987)) and can therefore be very important in decision-making, especially under complex or uncertain conditions (e.g. (J. Isenberg 1984, Agor 1986)). Intuition is nonconscious and can "deal with systems more complex than those which can be figured out in our conscious minds" (Parikh 1996). Intuition is especially useful in situations where problems are poorly structured (Behling and Eckel 1991) or ill-defined (Parikh 1996), and when one is faced with conflicting facts or inadequate information (Agor 1986). Moreover, intuitive decision-making is fast; faster than rational decision-making (Dane and Pratt 2007). In ambiguous and uncertain situations, intuitive decision-making is often used in combination with rational decision-making (J. Isenberg 1984).

Chapter 3.5.2: Experience

Many researchers have investigated how people make decisions and how experience, i.e. "the knowledge or skill acquired by a period of practical experience of something"[9], is related to decision-making. However, until the emergence of the Naturalistic Decision Making (NDM) movement in 1989, this research focused primarily on optimal ways of decision-making in well-structured and carefully controlled environments (Klein 2008). Then, with the introduction of Naturalistic Decision Making which researches how people actually make decisions in real-world settings as opposed to artificial laboratory settings, other conclusions were drawn: people did not make decisions by generating and comparing option sets as was thought before the introduction of NDM, instead, people rely on prior experience to rapidly categorize situations and determine appropriate course of action (Klein 2008).

In some situations, such as situations that deal with extreme time pressure, experience is used to make good decisions without having to compare options: through a combination of intuitive pattern matching (see figure 26) and conscious mental simulation, experienced decision-makers look for the first workable, satisfactory option instead of trying to determine the best possible option (Klein, Calderwood et al. 2010). This type of decision-making is often used by people with experience: rarely do experienced people partake in the process of choosing among alternatives; instead, because of the pattern recognition process, usually the first option they consider is an effective one (Klein 2015).

Chapter 3.5.3: Expertise

Intuition is deeply rooted in expertise (Salas, Rosen et al. 2010) and has therefore been hailed as one of its defining features (Gobet and Chassy 2009). Expertise can be defined as having "high levels of skill or knowledge within a given domain" (Salas, Rosen et al. 2010). Through this definition, expertise differentiates itself from experience: expertise regards knowledge within a given domain, while experience is concerned with knowledge of something in general regardless of the domain. Nevertheless, this does not mean that experience cannot turn into expertise: when one acquires high level domain-specific knowledge through experience, experience can turn into expertise.

Expertise has been linked to the effectiveness of decision-making (Salas, Rosen et al. 2010). Expert decision makers use a combination of deliberative (i.e. *rational*) and intuitive processing to make decisions and solve problems (Salas, Rosen et al. 2010). Expertise is at the root of intuitive processing (Salas, Rosen et al. 2010): when the decision-maker is knowledgeable and experienced within a certain domain (i.e. he/she is an *expert*) and thus possesses the extensive experience and knowledge that is necessary to take advantage of intuitive processing (Salas, Rosen et al. 2010), the intuitive decision-making process is most likely to be effective (Hogarth 2001). Logically, when this person is taken out of their context of expertise, his/her intuition is most likely to be less useful; when this happens, deliberative processing takes over to evaluate how past experiences can be applied to the present context (Hoffman 2007, Salas, Rosen et al. 2010).

The combination of expertise and intuitive processing results in something that Salas et al. describe as 'expertise-based intuition'. See figure 27. They define this type of intuition as "intuition rooted in extensive experience within a specific domain" (Salas, Rosen et al. 2010). Expertise-based intuition uses relevant knowledge and experience from the specific domain. This knowledge consists of explicitly stated knowledge as well as tacit knowledge such as conceptual and procedural knowledge (Salas, Rosen et al. 2010). In addition, expertise can produce a large knowledge base, contributing to effective pattern recognition (see figure 26 on p.39), and automaticity, which refers to automatic task performance, i.e. the execution of a task without or with minimal conscious effort because of practical experience (Moors and De Houwer 2006, Salas, Rosen et al. 2010).

[9] Oxford University Press, 2019, Retrieved from https://www.lexico.com/en/definition/experience

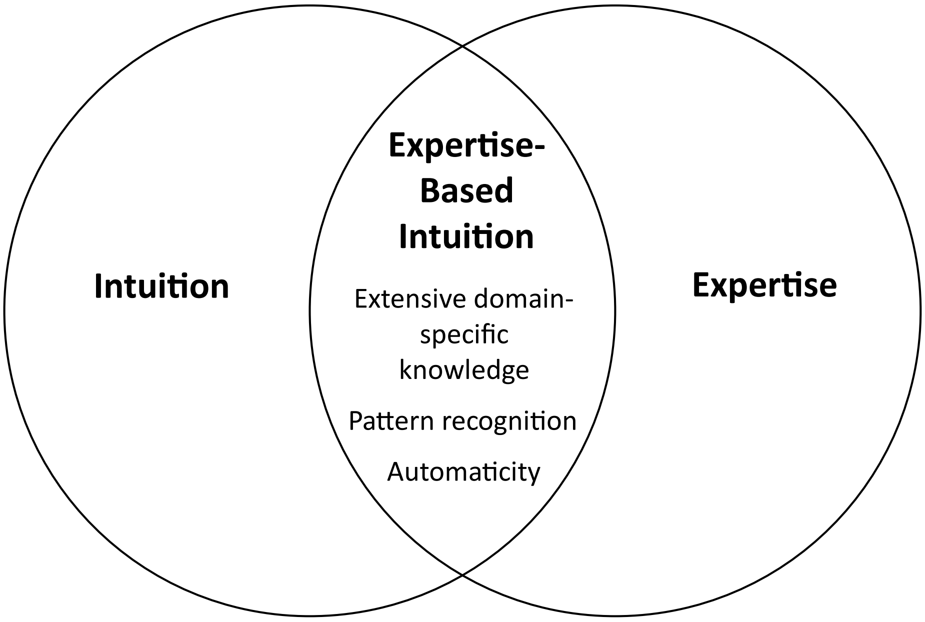


Figure 27: Venn diagram depicting the similarities between intuition and expertise – Based on (Salas, Rosen et al. 2010)

Chapter 3.6: Conclusion

This chapter has introduced Simon's concept of artifact to explain and define the products that are created during a product development cycle. These artifacts can serve as potential knowledge sources that can help individuals in decision-making and problem solving. However, to be of true value to an organization, this knowledge needs to be shared and articulated to make it accessible to other people. This process is explained in the next chapter. In addition to human-made knowledge sources, this chapter has also pointed out some non-human-made sources from which knowledge can be obtained. Intuition, experience, and expertise all contribute to effective decision-making and problem solving and are in some situations even preferred over rational decision-making.

As explained, artifacts can be used as a potential source of knowledge. Of course, this is not always their main function; although information artifacts are used for this purpose (i.e. providing information from which knowledge can be derived), this is not necessarily the case for social artifacts and technology artifacts. However, they can be used for this purpose as these artifacts can embed knowledge that was needed to create them (in case of technology artifacts), or because they embed knowledge that has arisen post creation (in case of social artifacts). Furthermore, the division between social artifacts, information artifacts, and technology artifacts as defined by Lee et al. is used because it is perceived to be very comprehensive and universal. Although it is tailored to the information-based development of physical consumer products, this division can easily be applied to the creation of, for example, intangible products or business goods. Thus, it is widely applicable to many types of product development organizations.

Chapter 4: Knowledge Creation Through Knowledge Conversion

Chapter 4.1: Introduction

The previous chapter describes three types of artifacts that arise during the development of a product. These artifacts are social artifacts, technology artifacts, and information artifacts. Knowledge can be derived from these artifacts, because they embed knowledge that is used to create them. As explained, this knowledge that is derived from artifacts can remain tacit, i.e. kept in people's minds, or made explicit by documenting it in books, documents, manuals, standards, etc. Moreover, it is mentioned that the term tacit knowledge can be attributed to knowledge that has not been made explicit (also called *expressible* tacit knowledge), as well as to knowledge that cannot be made explicit (also called *inexpressible* tacit knowledge). This chapter describes how *expressible* tacit knowledge can be made explicit and how it can be used to create new knowledge.

To create new knowledge from existing knowledge, existing knowledge must be managed and shared. Throughout the years, many researchers have investigated how knowledge can be created, shared and managed dynamically inside a company (e.g. (Nonaka 1991, Nonaka and Takeuchi 1995, Nonaka, Toyama et al. 2000, Teece 2000, Takeuchi and Hirotaka 2006)). Above all, efforts have been devoted to capturing the process and practice of knowledge management. Some examples of these efforts are the Wiig Model for Building and Using Knowledge by Wiig (Wiig 1993), the Knowledge Spiral Model created by Nonaka and Takeuchi (Nonaka 1991, Nonaka and Takeuchi 1995), and the Sense-making KM Model created by Choo (Choo 2006). These models all represent a holistic approach to knowledge management; however, these authors have different perspectives on how knowledge should be fostered in an organization. Wiig uses semantic networks to organize and create (new) knowledge, Nonaka and Takeuchi emphasize the interplay between tacit and explicit knowledge to create new knowledge, and Choo focuses on how information from the external environment is used in organizational actions.

This chapter explains how new knowledge can be created from existing knowledge. To accomplish this, the widely known Knowledge Spiral Model (Nonaka 1991, Nonaka and Takeuchi 1995) is used. Both the Wiig Model for Building and Using Knowledge by Wiig (Wiig 1993) and the Sense-making KM Model by Choo (Choo 2006) are either based on, or a further refinement of the knowledge creation theory by Nonaka and Takeuchi. Hence, it is chosen to adopt the knowledge creation theory by Nonaka and Takeuchi to manage and share existing knowledge and create new knowledge. Nonaka and his associates (Nonaka 1991, Nonaka and Takeuchi 1995, Nonaka and Konno 1998, Nonaka, Toyama et al. 2000) propose a spiral model for knowledge creation that consists of three elements: a) '*Ba*', the foundation for knowledge creation, b) SECI, the knowledge creation process, and c) knowledge assets, the inputs and outputs of the knowledge creation process. See figure 28. This chapter covers the first two elements and explains how they enable and contribute to knowledge creation. The last element, knowledge assets, is explained in chapter 5.

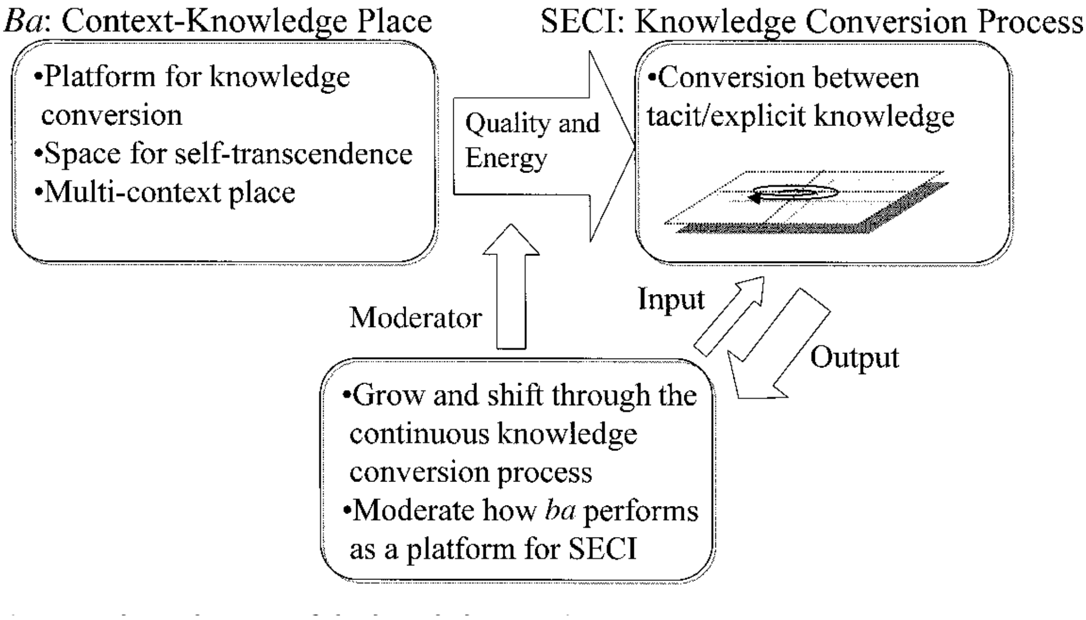


Figure 28: Three elements of the knowledge-creating process (Nonaka, Toyama et al. 2000)

Chapter 4.2 Knowledge Conversion

In the context of product development, i.e. the context where the product development processes take place, a lot of information and knowledge is created. To profit from this information and knowledge, information must be managed and shared (e.g. by means of an information management system) and knowledge must be shared and converted into new knowledge. To facilitate the creation and sharing of knowledge, the concept of *ba* is adopted. Subsequently, the SECI process is employed to convert tacit knowledge into explicit knowledge and vice versa. The foundation for knowledge conversion and the knowledge conversion process itself are explained in the following paragraphs.

Chapter 4.2.1: The Concept of *Ba*

During the development of a product, many processes take place that shape, create and add value to a product (see figure 22 on p.30). The processes that take place during product development need an environment or product development context to operate within. Moreover, an environment or setting is needed that facilitates the creation and sharing of knowledge. Thus, a foundation is sought that brings together the people that are involved in and execute these product development processes. The Japanese concept of '*ba*' adopted and elaborated on by Nonaka and Konno (Nonaka and Konno 1998) provides this foundation. As explained and depicted in figure 23 on p.32, information cannot be transformed into knowledge without a context. *Ba* serves as the context for individual and collective knowledge creation. *Ba* can be described as a "shared space for emerging relationships" (Nonaka and Konno 1998) in which knowledge is created, shared and utilized. This "shared space" does not need to be physical; although it can be a physical space such as an office, it can also be a virtual space such as a teleconference, and even a mental space such as shared experiences, or any combination of the above (Nonaka and Konno 1998). *Ba* might be confused with regular human interaction, however, *ba* differentiates itself from regular human interaction by providing a context for knowledge creation. The main difference between regular interaction and *ba* is that knowledge resides in *ba*. This means that knowledge can only be created in *ba* when individuals that participate in *ba* interact either among each other or with their environment (Nonaka, Toyama et al. 2000). To describe the interactions that take place in *ba*, four types of *ba* are defined: originating *ba*, which is characterized by individual, face-to-face conversations; dialoguing *ba*, characterized by collective, face-to-face conversations; systemizing *ba*, identified by collective, virtual interactions; and exercising *ba*, identified by individual, virtual interactions (Nonaka, Toyama et al. 2000). See Figure 29.

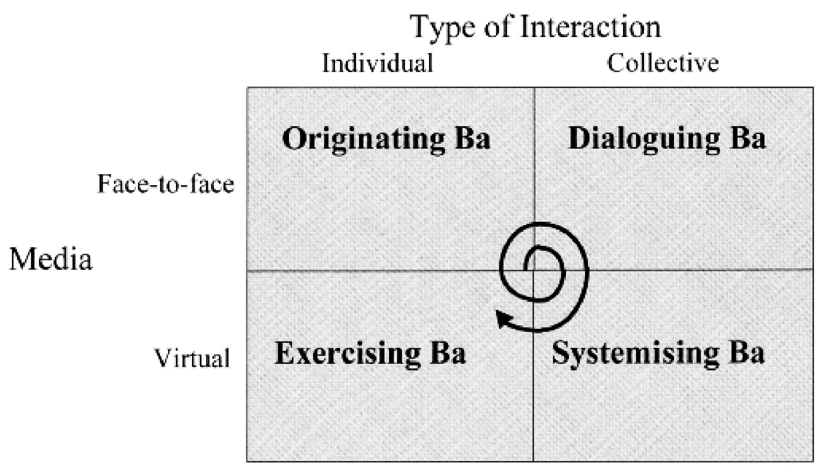


Figure 29: Four Types of *Ba* (Nonaka, Toyama et al. 2000)

The four types of *ba* each facilitate different interactions through different media. Firstly, originating *ba* is the *ba* in which the process of knowledge creation is initiated. It is the place where individuals share their emotions, feelings, mental models and experiences. This sharing of tacit knowledge can only be accomplished through face-to-face interaction, as this type of interaction is the only type of interaction in which the full spectrum of physical senses and psycho-emotional reactions can be captured (Nonaka, Toyama et al. 2000). In contrast to originating *ba*, dialoguing or interacting *ba* is the *ba* where individuals' mental models and experiences are converted into common terms and concepts. Dialogue among individuals is key, as it is the main enabler for this conversion (Nonaka and Konno 1998). Nonaka et al. add that "selecting individuals with the right mix of specific knowledge and capabilities is the key to managing knowledge creation in dialoguing *ba*" (Nonaka, Toyama et al. 2000). Systemizing or cyber *ba* is the *ba* where new knowledge (such as knowledge emanated from dialoguing *ba*) is fused with existing knowledge. Information technology enhances this conversion process by offering a virtual collaborative environment for the creation of systemizing *ba* (Nonaka and Konno 1998, Nonaka, Toyama et al. 2000). Lastly, exercising *ba* is the *ba* where new knowledge, communicated through virtual media, is embodied. This conversion is stimulated by focused training on routinized actions and the use of formal knowledge in real life or simulated applications (Nonaka and Konno 1998).

When individuals that participate in *ba* interact among each other or with their environment, new tacit and/or explicit knowledge is generated. When this knowledge is shared, i.e. it is separated from the *ba* it is created in, it turns into information which can then be communicated and disseminated independently from that *ba* (Nonaka and Konno 1998). The information and knowledge that is generated in each *ba* can then be used in decision-making processes. See figure 30. Information and knowledge that are generated in the product development context (consisting of different *ba*) are shared in the form of information and/or this information is stored and managed by an information management system. Through the decision-making process, information is transformed from one state to an altered state of that same information (see chapter 2.3.3). When this transformation and its effects are monitored and evaluated, knowledge can be obtained and converted to become new knowledge. This also emphasizes the pivotal importance of decision-making in product development. Apart from the SECI process explained in the following paragraph, decision-making is believed to be the only process that transforms information into knowledge. Although a lot of knowledge is created in a product development context, this knowledge, when it is extracted from its context, can only be shared in the form of information (because knowledge is context-specific, removing it from the context it is created in automatically turns it into information).

Figure 30 illustrates the flow of information within an information-based product development context. In different *ba*, information and knowledge are created by organizational members by performing development activities regarding the research and development and realization of a product. This information and knowledge is stored by an information management system in the form of information, and this information is subsequently reused by individuals that need information in order to make decisions or perform other development activities. This information is then transformed through decision-making (see chapter 2.3.3) and potentially turns into knowledge. This knowledge can then be stored in the information management system in the form of information, or it can then be embodied by organizational members and used in daily product development activities. Moreover, it can be converted to create new knowledge (see chapter 4.2.2). In this way, decision-making also enriches the organizational knowledge base (see chapter 5.2). The conversion of knowledge is explained in the following paragraph.

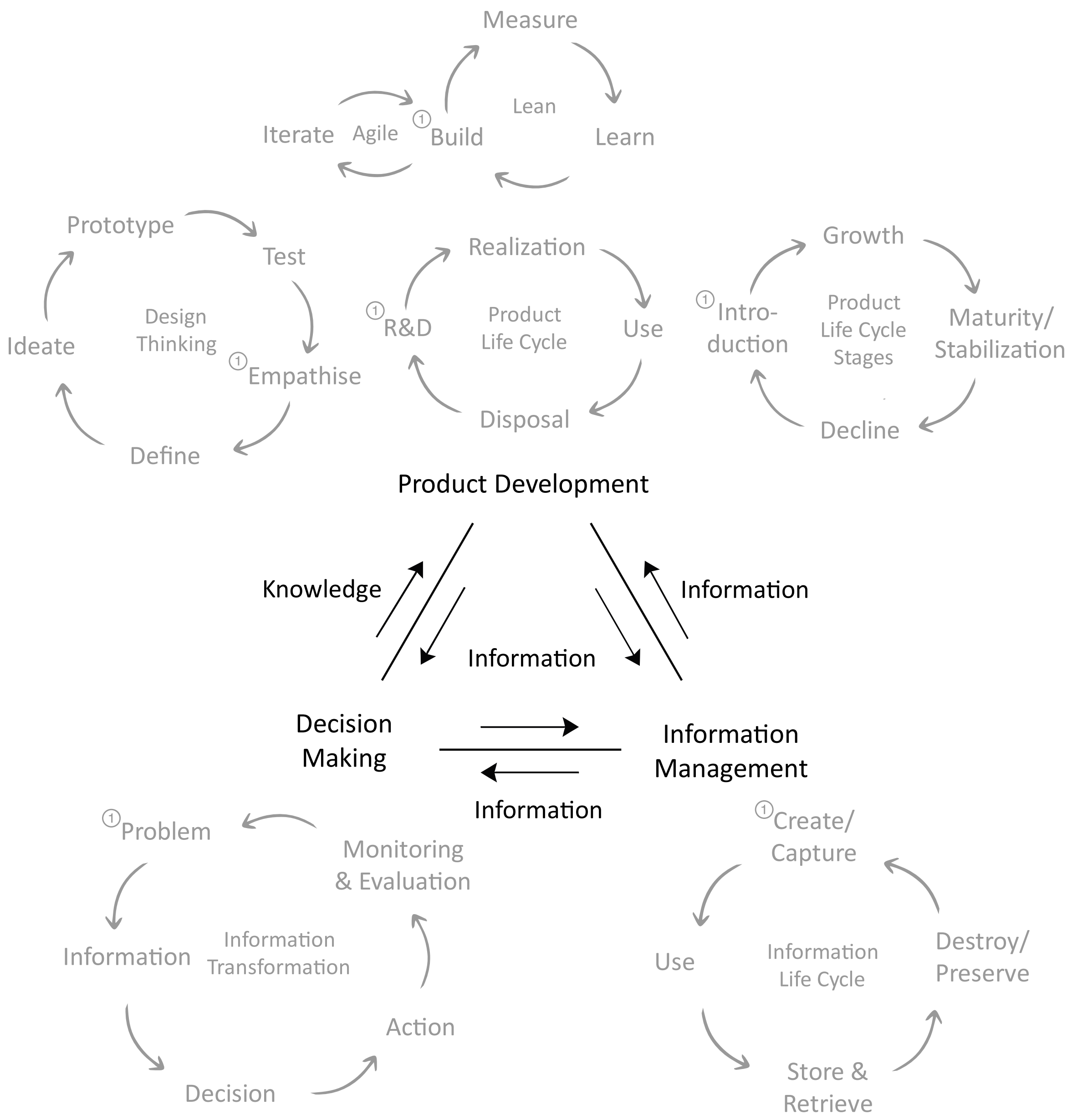


Figure 30: Flow of information and knowledge generated by PD activities

Chapter 4.2.2: The SECI Process

As described in the previous paragraph, *ba* offers the context for the knowledge creation process to take place. Four types of *ba* are described that facilitate individual or collective interactions through face-to-face interaction or a virtual medium. In contrast to *ba* that provides the context for knowledge creation, the SECI process offers the actual framework for the knowledge conversion process. Knowledge conversion provides a way for organizations to create knowledge through the interplay of tacit and explicit knowledge (Nonaka, Toyama et al. 2000). As mentioned in the previous chapter, knowledge is regarded as the most important element in decision-making and problem solving (Sharda, Frankwick et al. 1999). Therefore, knowledge creation and knowledge sharing should be a focal point in every organization. The SECI process describes four modes of knowledge conversion through which the knowledge creation process occurs. These conversion modes are socialization (the conversion from tacit to tacit knowledge), externalization (the conversion from tacit to explicit knowledge), combination (the conversion from explicit to explicit knowledge), and internalization (the conversion from explicit to tacit knowledge). See Figure 31.

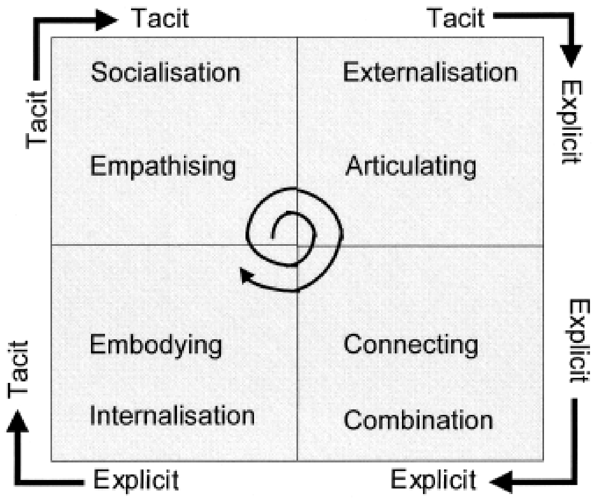


Figure 31: The SECI Process (Nonaka, Toyama et al. 2000)

As mentioned in the previous chapter, it is important to share knowledge; shared knowledge is more likely to be used than personal knowledge and decisions based on shared knowledge are usually of higher quality (Cruz, Boster et al. 1997). Nonaka and Takeuchi explain the process of knowledge conversion in detail in (Nonaka and Takeuchi 1995); this thesis provides a summary of the aspects of each conversion mode that are considered most important. Knowledge sharing is initiated by the socialization phase; socialization is the mode that starts off the knowledge conversion process and is facilitated by originating *ba*. In this phase, tacit knowledge is shared between participants of originating *ba* through individual, face-to-face interactions and results in new tacit knowledge (Nonaka, Toyama et al. 2000). Because tacit knowledge cannot be articulated (and even if it could be articulated in case of expressible tacit knowledge, it would turn into the transfer of explicit knowledge), this process of accumulating new tacit knowledge can only be acquired through shared experiences such as observation, imitation and practice (Nonaka 1991, Nonaka, Toyama et al. 2000). In contrast to the empathizing nature of the socialization mode, externalization is about expressing; externalization is facilitated by dialoguing *ba* and represents the mode where tacit knowledge is converted into explicit knowledge through collective, face-to-face interactions. For tacit knowledge to become explicit, it needs to be articulated; only then is knowledge crystallized and can it be shared with other people (Nonaka, Toyama et al. 2000). Articulation of tacit knowledge can be supported by several techniques that help to express this knowledge. Dialogue strongly supports externalization; therefore, techniques such as the use of metaphors, analogies and narratives can be used to express and translate highly personal or highly professional knowledge (Nonaka, Toyama et al. 2000). In addition, deductive reasoning, inductive reasoning and abductive reasoning can support externalization of tacit knowledge of customers and experts into knowledge that can be shared and managed (Nonaka, Toyama et al. 2000). This is of course only applicable to tacit knowledge that has not been made explicit yet; for tacit knowledge that cannot be made explicit, articulation is very difficult to impossible. Combination is the mode where (new) explicit knowledge (from e.g. the externalization phase) is combined with (new or existing) explicit knowledge from inside or outside the organization to form a new, more complex set of explicit knowledge (Nonaka, Toyama et al. 2000). Explicit knowledge can come from individuals and experts from within the organization, but also from customers and suppliers outside the organization. See figure 32. Moreover, this knowledge can also comprise public knowledge from other organizations (see chapter 4.3.4). By making use of virtual media such as computerized communication networks and large-scale databases, this new set of explicit knowledge can be disseminated quickly throughout the organization, making systemizing *ba* the perfect facilitator for this conversion mode. Newly created knowledge that is disseminated throughout the organization is personalized by individuals in the internalization mode. Internalization is facilitated by exercising *ba* and represents the mode where new explicit knowledge is embodied by members of the organization to become new tacit knowledge (Nonaka and Konno 1998, Nonaka, Toyama et al. 2000). Explicit knowledge can be internalized through action and practice (i.e. learning-by-doing) and then becomes part of an individual's tacit knowledge base. In addition, explicit knowledge can be internalized through simulations and experiments that trigger learning-by-doing (Nonaka, Toyama et al. 2000). Through internalization, an individual identifies which organizational explicit knowledge is relevant to oneself and internalizes this information, resulting in new personal (tacit) knowledge. This new tacit knowledge can then set off a new spiral of knowledge conversion through socialization (Nonaka and Konno 1998, Nonaka, Toyama et al. 2000).

When knowledge is shared and transformed through the four stages of the knowledge conversion process, the knowledge spiral becomes larger in scale as it moves up through the ontological levels (individual, group, and organization). Knowledge that is created through this knowledge spiral can trigger and even larger knowledge spiral (both horizontally as well as vertically) within an organization. As mentioned earlier, this knowledge spiral can transcend organizational boundaries: when (tacit) knowledge from customers or other organizations is fused with the existing organizational knowledge base, new knowledge can be created (Nonaka, Toyama et al. 2000).

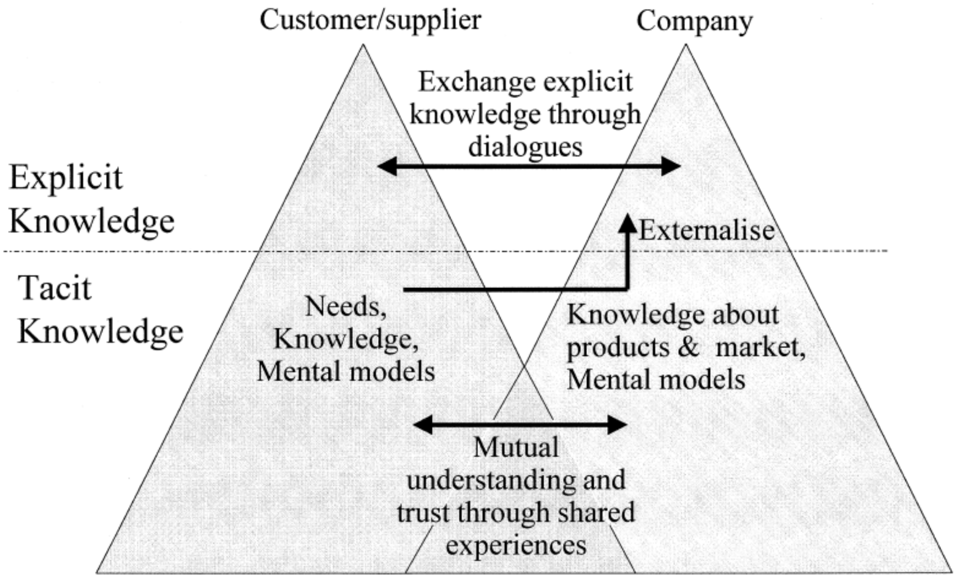


Figure 32: Creating knowledge with outside constituents (Nonaka, Toyama et al. 2000)

Chapter 4.3: Levels of Knowledge Conversion

The previous paragraphs describe how tacit knowledge can be converted into explicit knowledge and vice versa. A context that enables and stimulates knowledge creation is provided, as well as an actual framework for the creation of knowledge through knowledge conversion. This paragraph describes how knowledge can be created at different levels in an organization. These levels are the individual level, the group level, and the organizational level (Nonaka 1988, Takeuchi and Hirotaka 2006). The knowledge that is created at these levels within an organization is regarded as private, firm-specific knowledge (Yang, Fang et al. 2010). However, there is also a lot of knowledge created by other companies that resides in the public domain. This knowledge is referred to as public knowledge (Yang, Fang et al. 2010). Similarly to the conversion between tacit and explicit knowledge, public knowledge can be converted into private knowledge and vice versa, and can then be used by organizations to create new knowledge. Consequently, it is chosen to add one more level of knowledge conversion, which is the conversion of knowledge between organizations; therefore called the inter-organizational level.

Chapter 4.3.1: The Individual Level

Knowledge conversion starts at the individual level. Tacit knowledge held by individuals forms the basis for organizational knowledge creation (Nonaka 1988, Nonaka and Takeuchi 1995). According to Nonaka and Takeuchi, tacit knowledge is a "rich, untapped source of new knowledge" that enables knowledge creation. This personal tacit knowledge must be shared and converted to make it accessible to others (see chapter 4.3.2). When individuals that participate in *ba* (see chapter 4.2.1) interact with each other or with their environment, the knowledge creation process is initiated; at the individual level, individuals interact with their environment to form new personal knowledge. This personal knowledge can then be extended when tacit knowledge is converted into explicit knowledge (and vice versa) through the SECI process (see figure 31 on p.48). This extends the personal knowledge base and can improve the quality of decision-making. At the individual level, the process of socialization from the SECI model is particularly important: through personal one-on-one interactions such as observation and imitation, tacit skills and knowledge can be transferred directly from one person to another. Through socialization, the personal tacit knowledge base is enriched, and a new knowledge spiral is initiated.

Nonaka (Nonaka 1994) mentions that individuals need to be committed (i.e. "committed to recreating the world in accordance with [one's] own perspectives") to create new knowledge. He adds that there are three factors that induce individual commitment, which are intention, autonomy, and fluctuation. Firstly, intention is closely related to commitment. An individual must have intention, which can be described as an "action-oriented concept" that forms one's approach to the world and understanding of one's environment. The value of perceived/created information or knowledge lies not only in the nature of the information itself, but also depends on the intention of the person that receives and interprets it. Therefore, an individual's perception, context and prior knowledge affect the possibility of meaning and its form. Secondly, autonomy is important to achieve knowledge creation at the individual level; when individuals are given the freedom to make decisions and combine thoughts and actions, personal knowledge creation is stimulated. The interaction between an individual's perception and action is the basis for individual knowledge creation. Thirdly, knowledge creation at the individual level requires 'fluctuation'. Fluctuation can be described as discontinuity in the interaction between an individual and their environment. When discontinuities arise between an individual's knowledge and his/her perceived reality, one has to re-evaluate and re-create one's own system of knowledge. In this way, fluctuations or contradictions contribute to the creation of new personal knowledge.

Chapter 4.3.2: The Group Level

When new tacit knowledge is acquired by individuals through the socialization process, this knowledge needs to be shared to become more useful and valuable. As explained in chapter 4.2.2, externalization stimulates this process. When individuals interact with each other to share (new) tacit knowledge, the externalization process is initiated. To create knowledge among individuals, interaction is essential; within an organization, human interaction is best realized at the group level (Nonaka and Konno 1998). At this level, interaction is accomplished through dialogue or debate among individuals. In addition to encouraging dialogue and debate, autonomy (see chapter 4.3.1) can also be given at group level to stimulate the conversion from personal to organizational knowledge (Nonaka 1994). Similarly to autonomy at the individual level, autonomy at the group level stimulates self-government. This can enable the forming of self-organizing teams: project teams that take on a self-organizing character. Self-organizing teams stimulate knowledge creation by providing a shared context that encourages dialogue and the sharing of perspectives and experiences (Nonaka 1994). In addition to intention, autonomy, and fluctuation (also called "creative chaos" (Nonaka, Toyama et al. 2000)), *redundancy of information* and *requisite variety* play important roles in information creation, particularly at the group level. Redundancy of information, i.e. the intentional overlapping of information, promotes the sharing of tacit knowledge. By sharing redundant information, it becomes easier for people to understand the expression of tacit knowledge; when different perspectives on the same information are shared, it makes it easier for people to grasp what others are trying to articulate. Requisite variety comprises the balance between the creation of knowledge and its effective processing. This means that the diversity of organizational knowledge should match the environmental diversity it meets at any given time. To deal with the complexity of the environment, individuals in an organization should know who owns what information or knowledge, i.e. where it is located, and how it is accessed, without being exposed to all information at the same time to avoid information overload (Nonaka, Toyama et al. 2000).

To create knowledge at the group level, the five-phase model for organizational knowledge creation (Nonaka and Takeuchi 1995) can be used. This is a more practical model that integrates the SECI processes and involves the group by emphasizing interaction. This model resembles the design thinking processes (see figure 12 on p.17) but is knowledge-oriented instead of process-oriented. See figure 33. The five-phase model of the organizational knowledge creation process by Nonaka and Takeuchi incorporates the four knowledge transformations. Nonaka and Takeuchi describe all the phases in great detail in (Nonaka and Takeuchi 1995); this paragraph provides a summary that describes the most important elements, including a short explanation of how autonomy, intention, fluctuation, requisite variety, and redundancy of information are applied and used in each phase. The first phase, *sharing tacit knowledge*, corresponds roughly to the socialization process. In this phase, tacit knowledge is shared among multiple individuals with different backgrounds, perspectives, and motivations. Requisite variety is established through self-organizing teams and the requisite variety of its team members. Through this diversity, redundancy of information is created, and perspectives on organizational intention and shared. When management creates fluctuation and stimulates autonomy, individuals start to interact with their environment through which they accumulate tacit and explicit knowledge. The second phase, *creating concepts*, mainly relates to the externalization process. In this phase, tacit knowledge is converted into explicit knowledge by self-organizing teams. Autonomy must be encouraged to enable free thinking of individuals and divergence of ideas. Requisite variety provides different perspectives for solving problems and creating ideas. In contrast to the diverging nature of autonomy, intention helps convergence of ideas. Fluctuation and redundancy of information challenge team members to change their ways of thinking and to crystallize tacit knowledge, thus helping to create a common shared understanding among team members. The third phase, *justifying concepts*, assesses concepts against organizational intention. Redundancy of information provides different perspectives and can help in making informed, well-balanced judgements. In the fourth phase, *building an archetype*, the justified concept is converted into something tangible or concrete such as a prototype/mockup or conceptual model. This phase roughly corresponds to the combination process. Requisite variety can help to make sure that an archetype meets all requirements. Requisite variety and redundancy of information facilitate dynamic cooperation of multiple departments within an organization; organizational intention helps convergence of organizational know-how and technologies, as well as coordination of inter-departmental activities. The last phase, *cross-leveling knowledge*, mainly relates to internalization. This phase extends knowledge to other organizational divisions or outside constituents such as other organizations (e.g. universities, affiliated companies, distributors) and customers. Autonomy enables and stimulates internalization and transfer of new knowledge, while organizational intention directs it. (Internal) fluctuation facilitates internalization and knowledge transfer through disruptions in one's system of knowledge and, for example, through rotation of personnel. Information redundancy and requisite variety also enable and stimulate internalization and transfer of new knowledge.

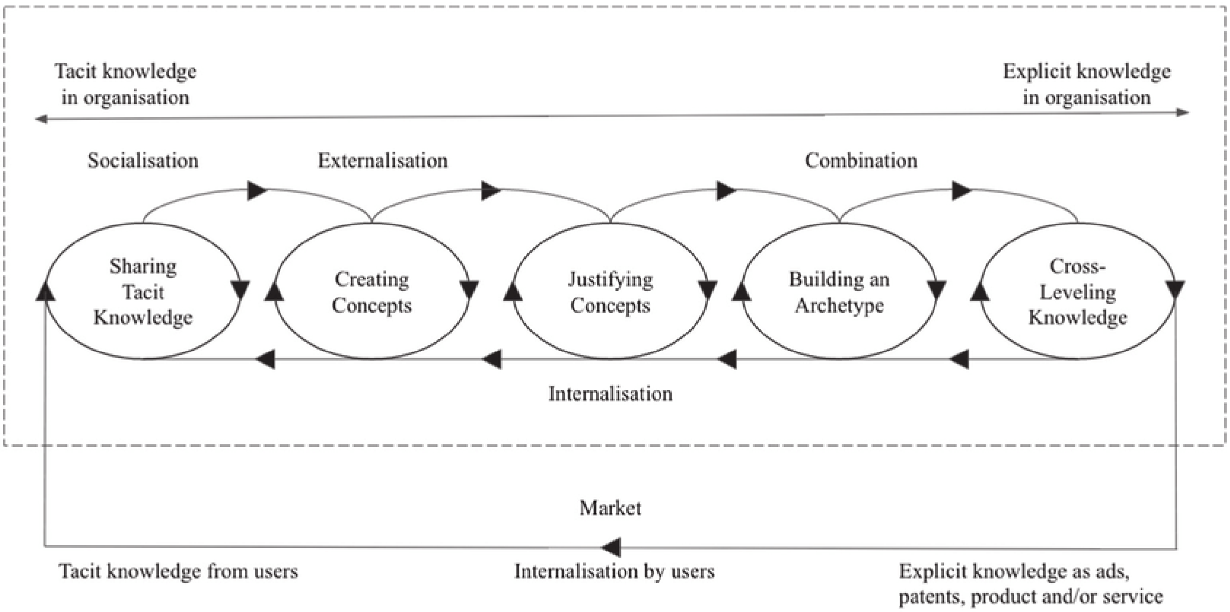


Figure 33: Five-Phase Model of the Organizational Knowledge Creation Process (Heikkinen 2018) based on (Nonaka and Takeuchi 1995)

Chapter 4.3.3: The Organizational Level

Knowledge that is created at the individual level and group level must be disseminated throughout an organization for effective use. In the most optimal way, this means that the right knowledge must be available to the right person at the right time and right place. This is a difficult task that poses a challenge for many organizations, as it cannot be accomplished through factors such as high speed an connectivity alone (Sharda, Frankwick et al. 1999). Sharda et al. state that connectivity does not guarantee the sharing of information and knowledge. Moreover, they note that connectivity can lead to information overload which subsequently distracts from the relevance of information. Nonaka and Takeuchi define organizational knowledge creation as "the capability of a company as a whole to create new knowledge, disseminate it throughout the organization, and embody it in products, services, and systems" (Nonaka and Takeuchi 1995). To achieve organizational knowledge creation and effective dissemination of knowledge throughout a company, structure is very important;

organizational structure manages groups and divisions involved in the process of information and knowledge creation and regulates relationships among them. To distribute resources among various departments and groups in an organization, the organization must know the needs and desires of groups and individuals regarding knowledge creation. In order to allocate and distribute resources such as people, money, information, and knowledge, an organization must know what resources are needed at what place. Thus, a structure must be established that stimulates information and knowledge sharing and subsequently distributes resources throughout an organization. A structure that can allocate resources based on information and knowledge sharing is found in figure 34.

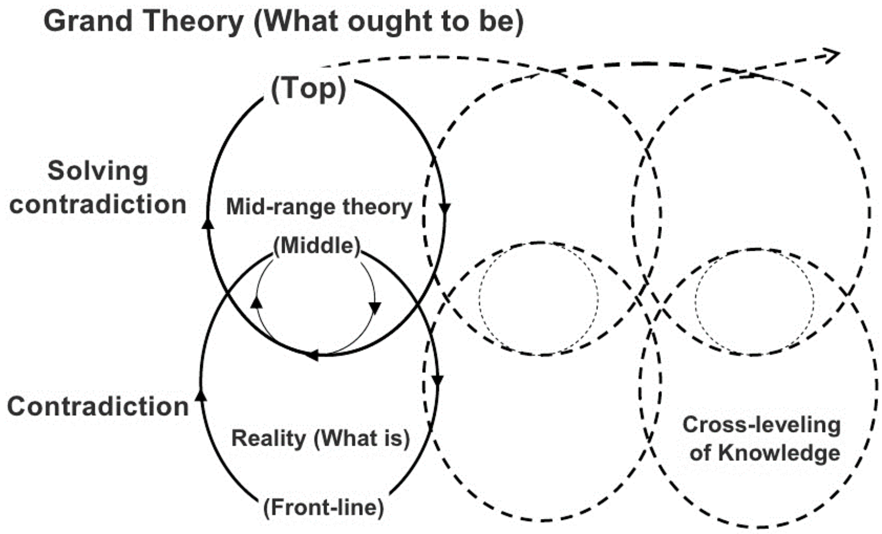


Figure 34: Middle-Up-Down Information Creating Process (Nonaka 1988)

Figure 34 describes the process of information sharing through middle-up-down management. Middle-up-down management disseminates information and knowledge throughout the entire organization, from top management to middle and lower management. As can be seen from figure 34, this process enables and stimulates information and knowledge flow throughout an organization. This information can regard, for example, contradictions in visions or dreams from top management and practical knowledge from lower management (Takeuchi and Hirotaka 2006). Top management provides a certain vision or sense of direction (i.e. *organizational intention*) that they want to achieve, but they do not necessarily know the current possibilities for realizing this vision. Lower management, i.e. the frontline workers, actually knows what exists at the moment and knows what is feasible. Middle management plays a central role in resolving these contradictions and bridges the gap between what top management hopes to achieve and what actually exists and is possible in the real world (Takeuchi and Hirotaka 2006). In order to solve contradictions, middle management translates the visions from top management into mid-range visions that are reflected and embodied in business and product concepts. These visions are subsequently realized at the group level (Nonaka 1994). As can be seen in figure 34, organizational knowledge creation can be considered as an spiral process that moves up the ontological levels of an organization, sometimes even reaching out to the inter-organizational level (Nonaka 1994). In addition to solving contradictions, the flow of resources (as depicted by the arrows in figure 34) can also be regarded as information and knowledge streams in general. An information or knowledge gap in top management can be filled by lower management and vice versa. Resource allocation then becomes allocation of information or knowledge to where it is needed. The conversion of knowledge then becomes the conversion from personal/group knowledge to organizational knowledge and vice versa.

Chapter 4.3.4: The Inter-Organizational Level

At the individual, group and organizational level, knowledge is created that can be labelled 'firm-specific' or 'private' knowledge, because it is unique and distinctive to an organization. However, there is also knowledge that resides in the public domain and is available to everyone, which can be called 'public knowledge'. Because private knowledge is unique and hard to imitate, it can be used to obtain competitive advantage (Yang, Fang et al. 2010). In contrast to private knowledge, public knowledge cannot be used as a source of competitive advantage because it regards knowledge that is easily available (Yang, Fang et al. 2010). The division of tacit and explicit knowledge can also be found in private and public knowledge and is supported by Yang et al.

Yang et al. (Yang, Fang et al. 2010) believe that knowledge is created through the interaction of an organization with their environment and they do not agree with Nonaka's theory of a knowledge spiral that starts at the individual level and spirals upwards to the organizational level. This view of organizational knowledge creation is not adopted in this thesis, but their theory is used in this thesis to describe knowledge creation at the inter-organizational level. Yang et al. introduce a model that describes the conversion from private knowledge to public knowledge and vice versa, which they call the 'EICE model'. This model consists of four modes of organizational knowledge creation, which are exploration, institutional entrepreneurship, combination, and exploitation. See figure 35. A short summary of each conversion mode is given based on (Yang, Fang et al. 2010). Firstly, exploration describes the conversion from existing private knowledge to new private knowledge. Through exploration, organizations stimulate the creation of new firm-specific knowledge and facilitate the transfer of existing private knowledge to different areas of an organization. New firm-specific knowledge can be created through, for example, research and development activities and innovation research, but it can also be created by fusing together previously separated private knowledge. Kogut and Zander define this as "combinative capabilities" of a firm, which is the ability to "generate new applications from existing knowledge" (Kogut and Zander 1992). Secondly, institutional entrepreneurship describes the process of converting private knowledge into public knowledge. Similarly to the externalization mode used in the SECI process (Nonaka and Takeuchi 1995), institutional entrepreneurship is concerned with the articulation of knowledge. When private knowledge is converted into public knowledge, it can be used by other organizations and can then enable new private knowledge creation for other organizations in the field, as well as for the organization that shared their private knowledge. Examples of institutional entrepreneurship are the standardization of new practices and the accomplishment of new technological standards. Thirdly, combination is the process of combining public knowledge with other public knowledge to form a new, more complex set of knowledge. Public knowledge can be several things, for example knowledge created by other organizations (e.g. suppliers, universities, etc.) that now resides in the public domain, but also knowledge emerging from the market space. Examples of public knowledge created by other companies are industry and occupational best practices such as lean management, just-in-time inventory management and total quality management, but also research reports, technical drawings, and manuals and textbooks. Examples of knowledge emerging from the market space are customer knowledge and feedback, and brand equity. Lastly, exploitation describes the conversion from public knowledge to private knowledge. When an organization acquires knowledge from outside their organization (i.e. the public domain) and integrates it with their own firm-specific knowledge, exploitation is initiated; examples of exploitation are cooperative organizational arrangements such as strategic alliances through which knowledge from partners is transformed into firm-specific knowledge, and other knowledge acquisition strategies that serve the same purpose. In sum, the fusion of public knowledge with private knowledge can enable the creation of new private knowledge, which can subsequently set off a new spiral of organizational knowledge creation.

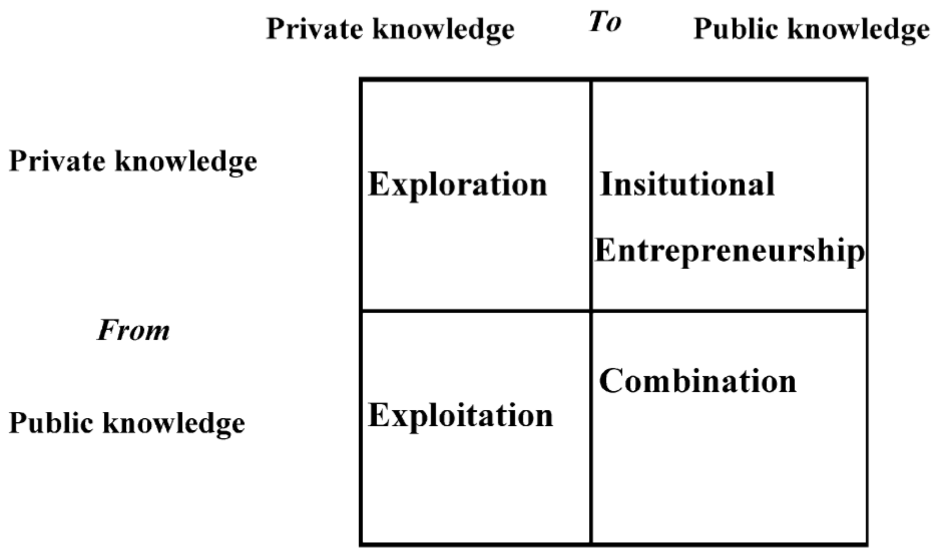


Figure 35: Modes of the organizational knowledge creation process (Yang, Fang et al. 2010)

Chapter 4.4: Conclusion

This chapter has described how new knowledge can be created from existing knowledge. The SECI process in combination with the concept of *ba* are the main enablers for knowledge conversion on the individual and group level. Through the SECI process, tacit knowledge is converted into explicit knowledge and vice versa; by converting tacit knowledge into explicit knowledge, it can be shared and managed. Knowledge creation at the organizational level refers to the sharing and management of knowledge and subsequently determining the flow of resources, among which are information and knowledge. At the inter-organizational level, private knowledge is converted into public knowledge and vice versa to stimulate the creation of new private knowledge. For clarification, several models have been presented that depict the process of knowledge conversion at each level of an organization.

This chapter has only made a distinction between tacit and explicit knowledge as in- and outputs of the knowledge creation process. However, a distinction can also be made between the types of knowledge regulating and moderating the knowledge creation process. Nonaka et al. (Nonaka, Toyama et al. 2000) refer to these types of knowledge as "knowledge assets". The next chapter explains the different knowledge assets in more detail and describes how they can be managed and shared.

Chapter 5: Management of Explicit and Tacit Knowledge

Chapter 5.1: Introduction

The previous chapters have identified several types of artifacts that are created naturally in product development and have explained how existing knowledge (for example knowledge derived from these artifacts) can be used to create new knowledge. As explained in chapter 3, artifacts embed knowledge; this can be personal knowledge about e.g. individual skills and know-how (captured by social artifacts), but also organizational knowledge such as knowledge derived from processes and routines (captured by information artifacts). The knowledge that is held by an organization can be referred to as the organizational knowledge base, and can be interpreted as the collection of organizational knowledge embedded in processes, procedures, routines, and structures (Teece 2000). This knowledge can be tacit as well as explicit and can be divided into different knowledge assets. Nonaka et al. define knowledge assets as ‘firm-specific resources that are indispensable to create value for the firm’ (Nonaka, Toyama et al. 2000). Knowledge assets serve as the inputs and outputs of the knowledge creation process and moderate this process (Nonaka, Toyama et al. 2000). When individuals interact to form new knowledge (e.g. through the SECI process), this knowledge then becomes part of the knowledge base of an organization, which in turn forms the basis for a new knowledge creation spiral (see chapter 4.2.2). Nonaka et al. create a division between four types of knowledge assets, which are experiential knowledge assets, conceptual knowledge assets, systemic knowledge assets, and routine knowledge assets (Nonaka, Toyama et al. 2000). For these knowledge assets to be utilized by members of an organization, they need to be managed and shared. Explicit knowledge assets are relatively easy to manage and share; tacit knowledge assets, on the other hand, are harder to manage as they are intangible and reside in the minds of people. This chapter explains the different types of organizational knowledge assets and mentions several techniques for managing explicit and tacit knowledge assets. Finally, a black box model is presented for the management of tacit knowledge.

Chapter 5.2: The Knowledge Base

According to researchers such as Nonaka et al. (Nonaka, Toyama et al. 2000), an organization's knowledge base is composed of knowledge assets. Knowledge assets have been stressed as the key to obtaining competitive advantage, now that physical assets such as tools and equipment no longer provide a source for significant differentiation (Teece 2000). Knowledge assets are intangible resources that serve as the inputs, outputs and moderators of the knowledge creation process (see chapter 4.2). Because knowledge assets are created through the knowledge creation process of an organization, they are unique and firm-specific and can therefore create value for a firm. According to Nonaka and Toyama (Nonaka and Toyama 2007) "*knowledge assets are not just the knowledge already created, such as know-how, patents, technologies, or brands, but also include the knowledge to create knowledge, such as organizational capability to innovate. Although current views on knowledge assets tend to focus on the former because they are easier to measure and deal with, it is the latter that need more attention because they are the source of new knowledge to be created, and therefore a source of the future value of the firm*." Nonaka et al. (Nonaka, Toyama et al. 2000) state that an organization's knowledge base consists of four types of knowledge assets, which are experiential knowledge assets, conceptual knowledge assets, systemic knowledge assets, and routine knowledge assets. Other researchers such as Morgan et al. use a similar division between experiential knowledge (i.e. "know-how", comprising experiential and routine knowledge assets) and informational knowledge (i.e. "know-what", comprising conceptual and systemic knowledge assets) (Morgan, Zou et al. 2003). The next paragraphs explain the different types of knowledge assets in more detail.

Chapter 5.2.1: Experiential Knowledge Assets

Experiential knowledge, as the name implies, is gained through experience and is deeply rooted in an individual's actions (Nonaka and Takeuchi 1995). Experiential knowledge assets are created and shared when tacit knowledge is transferred through experience. This sharing of tacit knowledge can be accomplished through, for example, the socialization phase in the SECI model (Nonaka and Takeuchi 1995). The experience that is the determinant for this type of knowledge asset can come from within an organization, but also from outside an organization such as tacit knowledge held by local communities, customers, suppliers, and other organizations. Experiential knowledge tends to be tacit and includes personal skills and know-how that allow required tasks to be executed in an efficient and effective manner (Morgan, Zou et al. 2003), but also other sorts of tacit knowledge such as emotional, physical, energetic, and rhythmic knowledge (Nonaka, Toyama et al. 2000). This knowledge can be converted through the externalization phase of the SECI process to become more tangible in the form of explicit knowledge. In addition, it can also be shared with other individuals in its original form of tacit knowledge (through socialization) to become more accessible among people. Because of its tacit nature, experiential knowledge assets are difficult to capture, manage and share. However, because they are firm-specific and unique and therefore difficult to imitate, they can form the basis for sustainable competitive advantage (Nonaka, Toyama et al. 2000).

Experiential knowledge is very important in product development, because is it very personal and therefore unique to every individual. Experiential knowledge includes aspects such as intuition and expertise and can thus be very helpful in decision-making and problem solving (see chapters 3.5.1 and 3.5.3). However, accumulating tacit knowledge is time-consuming and costly (Eriksson, Johanson et al. 1997, Teece 1998). Moreover, knowledge in general is of little value if it cannot be accessed by and/or supplied to the right people at the right time (Teece 2000). To make things even more complicated, experiential knowledge (and tacit knowledge in general) is difficult to transfer without the transfer of people (Teece 1998, Teece 2000) and some researchers even state that experiential knowledge cannot be transferred between firms or business units (Eriksson, Johanson et al. 1997). Thus, experiential knowledge is very important in organizations, but it is costly and time-consuming to acquire and even more difficult to transfer.

Chapter 5.2.2: Conceptual Knowledge Assets

Conceptual knowledge assets are characterized by explicit visuals such as images, symbols and language. Conceptual knowledge assets are based on concepts held either by the customer or by members of an organization. For example, a concept held by the customer is brand equity; though it has a tangible form, it still takes effort to understand what the customer perceives. For members of an organization, explicit concepts include product concepts and designs. In contrast to experiential knowledge assets that are difficult to transfer without the transfer of people (Teece 2000), conceptual knowledge assets are easier to grasp and transfer once it has been established what customers and members of an organization perceive (Nonaka, Toyama et al. 2000).

Based on a study that investigates the relationship among the four knowledge assets and the four phases of knowledge creation (chapter 4.2.2), Chou and He (Chou and He 2004) claim that conceptual knowledge assets have the most significant impact on the knowledge creation process. These researchers state that both the externalization and internalization phase are significantly influenced by conceptual knowledge assets. This thesis does not adopt this viewpoint in its entirety. Although it is agreed that externalization can be influenced by conceptual knowledge assets, this opinion is not shared regarding the internalization process. Because externalization is about expression and articulation, this type of knowledge asset can help with conceptualization by visualizing an idea or concept. However, by suggesting that individuals can internalize new knowledge through the use of conceptual knowledge assets, these researchers imply that new knowledge can be acquired through the creation of new concepts. This might be true, but it is a very process-oriented view on knowledge creation and moreover skips the socialization phase.

Chapter 5.2.3: Systemic Knowledge Assets

Systemic knowledge assets, in contrast to experiential and conceptual knowledge assets, are the most 'visible' type of knowledge assets, consisting of organized and packaged explicit knowledge (Nonaka, Toyama et al. 2000). Knowledge that is covered by this category of knowledge assets includes explicitly stated technologies and product specifications and manuals, but also intellectual properties such as patents and licenses. This category includes the information (i.e. explicit knowledge) that is captured and managed by an information management system. Because this type of knowledge asset is so tangible and distinct, knowledge that falls into this category can be transferred relatively easy. Moreover, because they are easier to measure and manage than other knowledge assets, current knowledge management mainly focuses on managing and protecting this type of knowledge asset (Nonaka, Toyama et al. 2000).

Interestingly, Chou and He claim that systemic knowledge assets have the least significant effect on the knowledge creation process (Chou and He 2004). They state that the combination phase is influenced by systemic knowledge assets, but they claim that experiential knowledge assets are of greater influence on the combination process. This statement is unfortunately not further elaborated upon by these researchers. Due to a lack of explanation and consequent lack of understanding of their point of view, this research does not adopt this claim. Instead, this research believes that systemic knowledge assets are of pivotal importance in the combination phase, as this phase combines new explicit knowledge with existing explicit knowledge (see chapter 4.2.2). Therefore, systemic knowledge assets and conceptual knowledge assets are important in the combination phase, because they are the only types of explicit knowledge assets. Moreover, because systemic knowledge assets are shaped as information artifacts (see chapter 3.4), this research believes that this type of knowledge asset is essential to create knowledge, as explicit and tacit knowledge can be obtained from it.

Chapter 5.2.4: Routine Knowledge Assets

Routine knowledge assets, similarly to experiential knowledge assets, consist of tacit knowledge that is gained through actions and practices (Nonaka, Toyama et al. 2000). Through current and past activities, certain patterns of thinking and action are reinforced and shared among individuals (Nonaka, Toyama et al. 2000). However, contrasting to experiential knowledge assets, routine knowledge assets are characterized by being practical; organizational know-how, organizational culture and organizational routines are part of this type of knowledge asset. An important aspect of routine knowledge assets is that they can hinder knowledge creation as well as foster it. Successful experiences and perceived best practices can lead to exploitation of current knowledge instead of exploration of new knowledge (March 1991). Maintaining an appropriate balance between exploitation of current routine knowledge assets and exploration of new knowledge assets is key.

Chou and He claim that routine knowledge assets mostly influence the socialization process (Chou and He 2004). They substantiate this claim by stating that the socialization phase, which refers to the process of converting new tacit knowledge through shared experiences, is process-oriented. This thesis adopts the viewpoint that routine knowledge assets are acquired through the execution of certain processes and are therefore process-oriented, but it dismisses the claim that the socialization phase is process-oriented. Undoubtedly, the socialization phase regards activities and processes through which tacit knowledge is shared. However, as this research focuses on information-centered product development, it is of the upmost importance that the focus is put on the information and knowledge that is being transferred instead of on the processes that enable the sharing of tacit and explicit knowledge. Consequently, the socialization phase becomes a content-oriented phase that is stimulated by routine knowledge assets.

Chapter 5.3: Managing Explicit Knowledge

Explicit knowledge, such as conceptual knowledge assets and systemic knowledge assets, is relatively easy to manage. Explicit knowledge consists of information placed and interpreted in a certain context. By definition, explicit knowledge can be easily articulated and communicated in numbers and text. Therefore, it can be efficiently managed and shared through, for example, an information technology (IT) system. Many techniques for managing and utilizing explicit knowledge can be found throughout literature and are used by organizations in everyday life. For example, Wyatt mentions several techniques for managing codified i.e. explicit knowledge, which are practice guidelines, decision support systems, reference databases, and the Internet (Wyatt 2001).

According to a literature review executed by Liao (Liao 2003), knowledge management techniques/ technologies can be classified into seven categories, which are knowledge management (KM) frameworks, knowledge-based systems, data mining, information and communication technology, artificial intelligence systems/expert systems, database technology, and modeling. This literature review is executed several years ago but is still considered relevant. A short description and some examples and applications that are mentioned in this literature review are provided to get an idea of each technique. The first category, KM frameworks, deals with providing an overall framework for managing knowledge by describing definitions, concepts, activities, stages, circulations, and procedures covered by knowledge management. An example of a knowledge management framework is 'The Knowledge-Creating Company' by Nonaka and Takeuchi (Nonaka and Takeuchi 1995) that explains several aspects of the knowledge creation and knowledge management process. The concepts of knowledge assets and intellectual capital are other examples of knowledge frameworks. The second category, which regards knowledge-based systems, is a human-centered approach that has its roots in artificial intelligence (AI). This is a very broad category that includes information technology that facilitates the management of organizational knowledge assets. Examples are AI systems, expert systems, rule-based systems, groupware, and database management systems. The next technique is data mining. Data mining combines the fields of AI, computer science, machine learning, database management, data visualization, mathematic algorithms, and statistics in order to 'mine' new explicit knowledge from databases. Thus, data mining technologies are aimed at discovering knowledge in databases, often with the purpose of providing decision support. Examples of data mining techniques are latent semantic indexing (LSI) for mining consumer product data, and knowledge warehousing that integrates functions of knowledge management, data warehousing, AI, and decision support. The fourth category, which covers information and communication technologies, combines information computing and network technologies in order to process and share information and explicit knowledge. ICT provides a platform for exchanging information and knowledge, while digital networks establish connectivity between organizational members that supports collaborative decision-making, organizational learning, and organizational memory. A very well-known example of an information and communication technology is the Internet, which, together with some other network technologies and services, forms am environment for rapid knowledge creation. The fifth technology, expert systems, regards systems and programs that capture knowledge, more specifically human expertise, through artificial intelligence. An expert system typically consists of the knowledge base (see chapter 5.2) and the expert system shell that processes the inputs and outputs of the expert system (Emmanuel and Adekunle 2013). Expert systems can support decision-making by asking relevant questions and subsequently providing potentially relevant information. The sixth category comprises database technology. Database technology facilitates the efficient management of a collection of centralized data. A database management system provides the software that centralizes and manages data, and thus enables information and knowledge sharing. However, redundant data can hinder the search for important information, and thus redundant data needs to be minimized to ensure efficient and effective management of data. This can be accomplished through, for example, multi-dimensional data analysis and online analytical processing. The last technique that can be helpful in managing explicit knowledge is modeling. Modeling technologies provide quantitative methods for analyzing objective and subjective data, and subsequently help to represent and acquire knowledge. Some examples of modeling applications are process modeling, cognitive modeling, knowledge value modeling, intangible assets modeling, and mathematical modeling.

In conclusion, there are many different frameworks, techniques, and technologies that enable and support the management of explicit knowledge. Many of these methods and applications are focused on solving similar types of problems regarding knowledge discovery, knowledge sharing, knowledge refinement, and knowledge acquisition. In addition, different technologies can have common concepts and types of methodology. For example, database technology can employ similar functionalities and concepts as those used in data mining; knowledge-based systems can overlap with artificial intelligence/expert systems in purpose and functionality, because AI and expert systems are a particular example of knowledge-based systems. Which technology is relevant in a certain context depends on the situation and the desired result.

Chapter 5.4: Managing Tacit Knowledge

In contrast to managing explicit knowledge, managing tacit knowledge is very difficult to impossible. Expressible tacit knowledge (i.e. tacit knowledge that can be made explicit but has not (yet) been made explicit) can be articulated and managed; however, it then turns into explicit knowledge and simply becomes the management of explicit knowledge. Mohajan mentions that ICT can facilitate the sharing of expressible tacit knowledge through e.g. expert systems, tele- and videoconferences, intra- and extranets, e-mail, databases, and groupware (Mohajan 2016). ICT can be useful especially in geographically distributed environments, but it cannot replace face-to-face interactions (Mohajan 2016). Another example of research that uses ICT to manage expressible tacit knowledge is the framework created by Al-Qdah and Salim (Al-Qdah and Salim 2013). These researchers have created a framework that transfers expressible tacit knowledge through ICT perspective based on the level of tacitness of the knowledge one (the expert) wants to transfer, and the media richness theory. From these examples, it becomes clear that IT/ICT can be used to capture, store and share expressible tacit knowledge. This is however not the same for inexpressible tacit knowledge; because it cannot be expressed, it cannot be codified and managed. Inexpressible tacit knowledge can only be shared and transferred through face-to-face interactions (Nonaka, Toyama et al. 2000); thus, the transfer of tacit knowledge requires socialization (Shailesh and Gupta 2012). Al-Qdah and Salim (Al-Qdah and Salim 2013) have identified several mechanisms that enable and facilitate the transfer of this type of knowledge. Some of these mechanisms are presented now.

Firstly, a Community of Practice (CoP) enables the sharing of tacit knowledge by creating a context for social learning (Wenger 1998). Wenger defines a community of practice as "a living context that can give newcomers access to competence and also can invite a personal experience of engagement by which to incorporate that competence into an identity of participation" (Wenger 1998). A community of practice consists of an informal network of people "bound together by shared expertise and passion for a joint enterprise" (Wenger and Snyder 2000). New knowledge is created in a community of practice when experiences and current knowledge are shared. Secondly, apprenticeships and mentoring allow tacit knowledge to be shared between master and pupil. During an apprenticeship, an apprentice obtains tacit knowledge from an expert through practical, hands-on experience (Clarke 2010). Similar but not identical to an apprenticeship, a mentoring dyad can serve as the context that enables the sharing of tacit knowledge (Engström 2003). As Engström explains, "a mentoring dyad [does] not only establish a context with care and trust but also enables sharing of tacit knowledge through important face-to-face conversation and interaction". The difference between apprenticeships and mentoring dyads is that apprenticeships are based on profession and regard knowledge about a particular craft; in contrast, mentoring focuses on obtaining valuable wisdom and advice, independent of the craft. Thirdly, observations and learning-by-doing are closely related to communities of practice, and apprenticeships and mentoring. Tacit knowledge that is shared and obtained through observation in communities of practice, and apprenticeships and mentoring, must be used and applied to become part of the personal knowledge base. Leaning-by-doing is pivotal to internalize new knowledge (Nonaka, Toyama et al. 2000). Other examples mentioned by Al-Qdah and Salim to transfer and utilize tacit knowledge in an organization are metaphors and analogies, storytelling, brainstorming, expert interviews, best practices, lessons learned, concept (cognitive) maps, and casual maps. For more information about these mechanisms, see (Al-Qdah and Salim 2013).

In literature and practice, several technologies can be found for the efficient and effective management of explicit knowledge (see chapter 5.3) and expressible tacit knowledge. However, this is not the case for inexpressible tacit knowledge. As explained, inexpressible tacit knowledge is elusive by nature. Therefore, managing inexpressible tacit knowledge is, by definition, impossible. Moreover, even if expressible tacit knowledge is made explicit, it loses much of its intrinsic meaning and value as it is highly personal and context-related (Kakabadse, Kouzmin et al. 2001). Kakabadse et al. add that "even if knowledge has been articulated into words or mathematical formulas, this explicit knowledge must rely on being tacitly understood and applied" (Kakabadse, Kouzmin et al. 2001). Moreover, individuals may not possess the skills or motivation to articulate their useful knowledge, or resist to do so (Sanchez 2005). However, knowledge that is not articulated and that remains tacit in the minds of people may disappear from an organization when individuals become incapacitated, retire, leave the organization, or are recruited by competitors (Sanchez 2005, Mohajan 2016). Due to expressible tacit knowledge losing its meaning when articulated, and the unarticulatable nature of inexpressible tacit knowledge, tacit knowledge should not and cannot be forced to be made explicit to be able to manage it. So how can tacit knowledge be managed without having to articulate it? Firstly, knowledge can be transferred by transferring people within an organization. However, this is often costly and time-consuming and may be resisted by organizational members (Sanchez 2005). Therefore, this option is not preferred. Secondly, instead of moving people and unsuccessfully trying to make tacit knowledge explicit, one could try to locate and manage the *source* of (relevant) tacit knowledge, or at least come as close to the source as possible. However, finding the source of tacit knowledge might be hard, as the tacit knowledge itself is not visible. Moreover, Teece adds that "merely finding the person or group with the knowledge one needs is often quite difficult" (Teece 2000). Thus, an aid is needed that helps to find this source indirectly. Instantiations (see chapter 3.4) and *effects* of tacit knowledge one possesses may be visible/explicit and may be used to find its source. These effects create an expectation of where tacit knowledge resides and increases the chance of finding its source. It should be noted that even when one finds the source of certain knowledge, one is not guaranteed to gain the knowledge one is searching for. A short example is provided to further clarify this view. The example describes a rain cloud and the rain coming from this cloud. The cloud itself is elusive and cannot always be observed by the human eye. However, the rain coming from the cloud can be observed and felt and affirms that there must be a cloud, even if it cannot be observed. Searching for the rain brings one closer to the cloud. Standing in the rain brings one as close to the cloud as possible. Yet, feeling the rain does not mean that one knows for sure from which cloud the rain comes; one just knows that there is a cloud. In this example the cloud resembles the intangible, tacit knowledge. Like tacit knowledge, it is elusive and imperceptible to the human eye. The rain matches the *effects* or *consequences* of the cloud being present; because there is rain, there *must* be a cloud. Explicit knowledge, in this example represented by the rain, can be used to find tacit knowledge, in this example illustrated by the cloud. Because this option cannot provide a person with clear information about the source of specific knowledge, it is not advised to use this option alone. However, it can be used in combination with the next option. Thirdly, tacit knowledge can be managed by creating overviews of which person has interacted with which knowledge (areas). By managing the documents an individual has interacted with in a given time period, it can be estimated what knowledge an individual possesses. In this way, the effects of having interacted with certain knowledge areas can be managed, without having to articulate what these effects (e.g. knowledge and competences) are. The next paragraph explains how explicit knowledge can be used to obtain (relevant) tacit knowledge.

Chapter 5.5: A Black Box Model for Managing Tacit Knowledge

As mentioned in paragraph 5.3, explicit knowledge is relatively easy to manage through IT systems. This is unfortunately not the case for tacit knowledge (see chapter 5.4). As explained before, inexpressible tacit knowledge cannot be managed the same way as explicit knowledge would be managed by an IT system. However, an IT system could provide explicit information of where (relevant) tacit knowledge might be found (see chapter 5.4). Moreover, because of the efficiency of IT systems, a solution is sought that can share and manage tacit knowledge by using such a system. To demonstrate how tacit knowledge can be managed through IT, a black box model is used. In contrast to a practical application, a black box model is context-free and can be viewed in terms of inputs and outputs, without knowledge of the internal workings (the implementation is "black"). In this research a black box model is preferred over a practical application, because a general, context-free solution is sought for the management of tacit knowledge. Moreover, by providing a black box model, the applicability of the solution is extended, as it is not limited to a certain context or limited to solving a specific problem (within an organization). To clarify how such a system may work, an example is provided. Imagine a librarian who helps people to find relevant knowledge in a library. Based on tacit and explicit knowledge obtained through experience, the librarian can point one in the right direction of the knowledge one is searching for. Because books are labelled to belong to certain categories (e.g. genre, language, etc.), the librarian knows where certain knowledge can be found. Even if the librarian does not know for sure where knowledge can be found, he/she can for example exclude categories that are certainly not relevant, or he/she can point out similar subjects. In this way, the librarian provides explicit knowledge of where relevant knowledge can be found. Nevertheless, this does not guarantee that the person searching for knowledge will find one's answer exactly there where the librarian has pointed him/her, but one is more likely to find his/her answer now that he/she has interacted with the librarian. These principles are also the basis for the black box model.

As mentioned before, knowledge is of little value if it cannot be accessed by and/or supplied to the right people at the right time (Teece 2000). Thus, the *right information* (i.e. explicit knowledge) must able to be delivered to the *right person*, at the *right time*, and in the *right format* and *right quantity*. Information is not always interpreted in the same way: how it is interpreted depends on the context and on the person receiving the information. The same information might be interpreted differently in different contexts. Moreover, the same information can be interpreted differently by different people due to, for example, their background, culture, or expertise. However, *where* something can be found is not ambiguous or subject to interpretation. The source of knowledge can be a virtual source or a physical source. A virtual source is for example an electronic document. A physical source can be a paper document or book, but also a human being. What source of knowledge is relevant depends on the knowledge that is sought: knowledge derived from practical information might be efficiently obtained through (electronic) books and documents, as opposed to knowledge derived from experience that might be more effectively obtained through interaction with an experienced individual. When the source of certain knowledge is located, it must be delivered to the right person, i.e. the person that uses the system (in this case the black box system) to find knowledge. To achieve this, organizational members must be able to have access to information and knowledge. However, this does not mean that all individuals must be able to have access to all information/knowledge within an organization. When providing the source for certain knowledge, access must be granted to that source either directly or indirectly (e.g. by obtaining permission through explanation of importance). Moreover, when the source of knowledge is an individual, accessibility to information or knowledge is not relevant because it does not regard direct access to this information/knowledge; it only regards access to people holding information/knowledge. In addition, information must be delivered at the right time. This means that information must be able to be supplied to the right person at any time during product development when certain knowledge is needed. The system must always be accessible particularly during product development when a lot of information and knowledge is needed to make good decisions, and possibly during the whole life cycle of a product to increase the overall efficiency and effectiveness of product life cycle processes. Moreover, this information must be delivered in the right format and quantity; whether the source of knowledge is physical or virtual, the right format of where specific knowledge might be found (e.g. paper documents, electronic documents, audio, video, etc.) and the right quantity of information necessary to find the source must be provided to the person seeking this knowledge. To find (or come as close as possible to) the source of specific knowledge, the information provided by the system regarding the source must be as complete as possible.

Figure 36 depicts the black box model that is described in this paragraph. It illustrates several (tacit) knowledge sources (in no particular order) and the output of the system, that is, explicit knowledge of where to find (relevant) tacit knowledge. The system enables knowledge sources to be recognized and shared in the form of explicit knowledge. How the system labels and categorizes knowledge is explained in chapter 6.

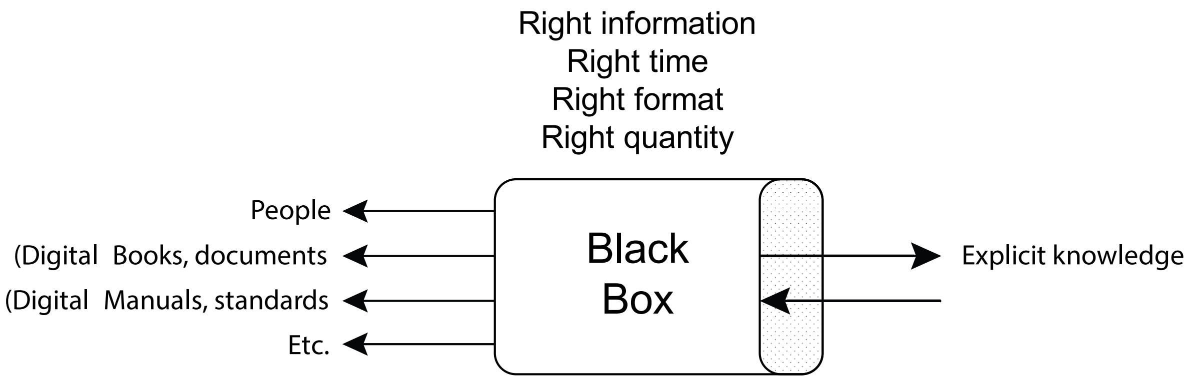


Figure 36: A Black Box Model for Managing Tacit Knowledge

Chapter 5.6: Conclusion

This chapter has described several organizational knowledge assets that, when they are managed, shared and reused, can create a knowledge flow that helps to achieve organizational objectives such as innovation, competitive advantage, and continuous growth. Moreover, this chapter describes how these knowledge assets can be managed by using the efficiency and effectiveness of an IT system. Many technologies for managing explicit knowledge already exist and are being used by companies and other organizations. Tacit knowledge cannot be managed in a traditional way as it cannot be articulated. In order to manage tacit knowledge through information technology, a black box system is proposed that manages tacit knowledge by providing explicit knowledge of where (relevant) tacit knowledge can be found. In other words, a system is proposed that manages sources of both tacit and explicit knowledge. The next chapter explains how this black box model is used for this purpose.

Chapter 6: A Black Box System for Knowledge-Driven Development

Chapter 6.1: Introduction

The goal of this thesis is to equip product developers with a system that provides them with relevant tacit and explicit knowledge at any given time during a product's life cycle. The focus is on obtaining relevant tacit knowledge by using explicit knowledge of (potential) knowledge sources. As described in the previous chapter, a black box model is used for this purpose. As can be seen from figure 36 on p.66, this black box model is fairly straightforward and relatively simple. This is because it is designed to facilitate/help in every decision a product developer has to make during a product's life cycle (and especially during product development), and thus it must cater to a wide range of different contexts. Moreover, it is a relatively simple model because it captures the essence of product development: creating and obtaining knowledge to make well-founded decisions and solve problems. The black box model presented in figure 36 on p.66 is part of a larger scheme briefly addressed in chapter 1.3. See figure 37 (a larger image of the scheme can be found on the next page). This scheme places the black box system within the context of product development. More importantly, it is placed at the center of product development, serving as a bridge between the information and knowledge created in product development contexts and the product developer who needs information and knowledge to make decisions and solve problems. Figure 37 provides an overview of the core of product development: in sum, product developers need relevant information and knowledge to quickly answer questions and make decisions; this information and knowledge originates from product development contexts and is provided to users through the black box system. This chapter describes how the proposed black box system provides product developers with (potentially) relevant information and knowledge.

In order to explain how the black box system provides tacit and explicit knowledge to its users, it is important to reiterate on some key features of tacit knowledge. Because tacit knowledge is inherently personal and largely remains tacit in the minds of people, the importance of people as "knowledge carriers" has been stressed (Teece 2000, Sanchez 2005). As a consequence, the transfer of people has been emphasized to disseminate tacit knowledge throughout an organization (e.g. (Teece 2000, Sanchez 2005, Mohajan 2016)), but as explained, this is costly and time-consuming (Sanchez 2005). As mentioned in chapter 5.5, an IT system can be helpful in managing sources of tacit knowledge. For example, information technology can be used to catalogue expertise of organizational members and consequently facilitate access to the right people at the right time (Hawamdeh 2002). Accordingly, more attention must be paid to the people who actually create and possess knowledge ("knowledge creators" and "knowledge carriers") in order for knowledge management (technologies) to be successful (Hawamdeh 2002, Olomolaiye and Egbu 2005). The first essential step in managing tacit knowledge is identifying who possesses what knowledge in an organization (Sanchez 2005). Then, knowledge needs to be labelled to be able to connect/allocate it to individuals. When knowledge is labeled (i.e. it is defined which knowledge is possessed by which individuals) and allocated, the system can provide product developers with potentially relevant (tacit) knowledge sources. This is further explained in the in the following paragraphs.

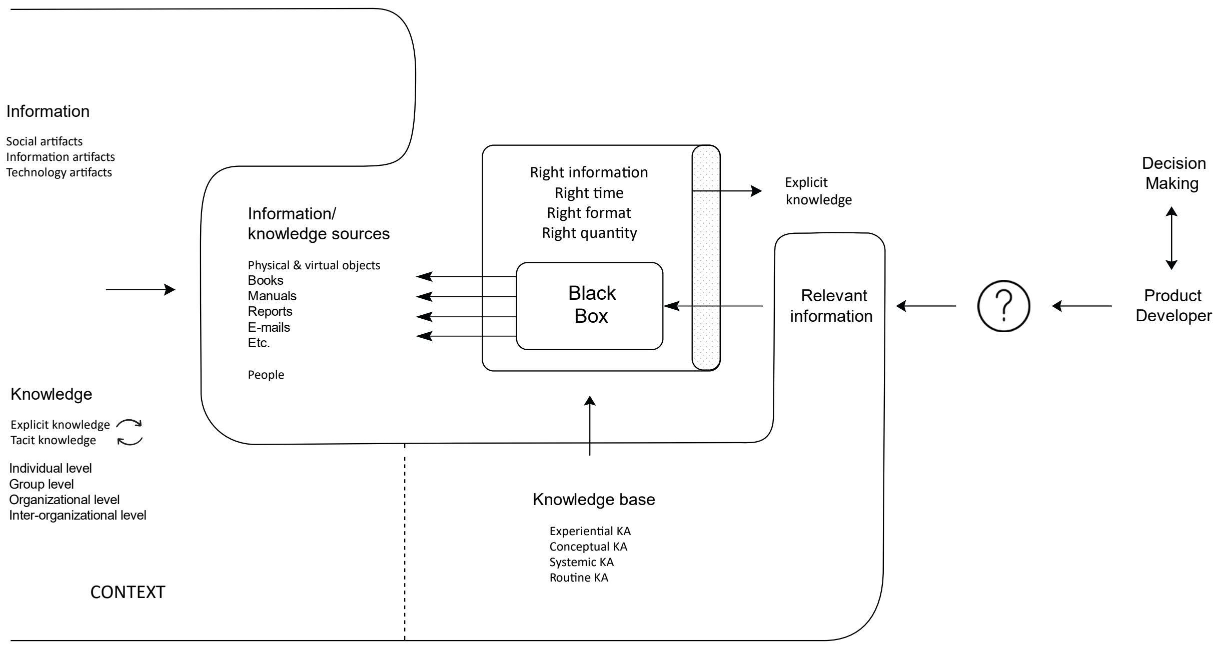
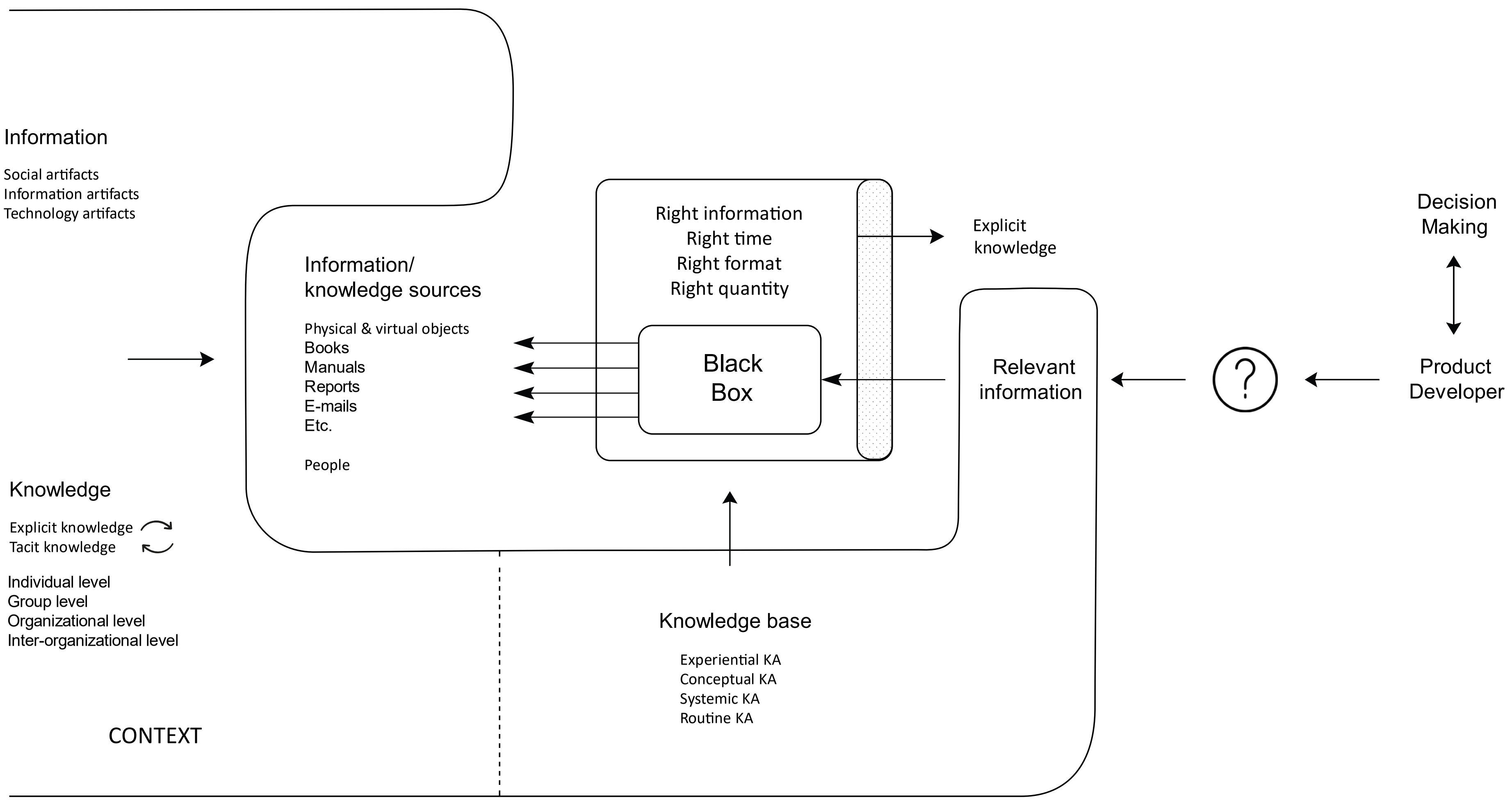


Figure 37: The proposed black box system placed within product development context


Information
Social artifacts
Information artifacts
Technology artifacts
Information/
knowledge sources
Physical & virtual objects
Books
Manuals
Reports
E-mails
Etc.
People
Right information
Right time
Right format
Right quantity
Black
Box
Explicit
knowledge
Relevant
information
Decision
Making
Product
Developer
Knowledge
Explicit knowledge
Tacit knowledge
Individual level
Group level
Organizational level
Inter-organizational level
Knowledge base
Experiential KA
Conceptual KA
Systemic KA
Routine KA
CONTEXT

Chapter 6.2: Labeling Tacit Knowledge

To label knowledge of organizational members, an organization must identify which individual possesses what knowledge; this is the basis for tacit knowledge management. However, determining which individual possesses what knowledge can be difficult; because tacit knowledge cannot be articulated, individuals cannot express which knowledge they possess (subconsciously) or how knowledgeable they are. Even if they could articulate what knowledge they possess, individuals may claim to have knowledge they don't actually have, or they may claim to be more knowledgeable then they really are (Stein and Ridderstråle 2001). Thus, tacit knowledge sources need to be labeled in a different way. This paragraph makes a distinction between people as the source of tacit knowledge, and other physical and virtual sources of tacit knowledge, such as (digital) books, manuals, standards, reports, e-mails, and so on. In addition, this research focuses only on objects that consist of written natural language text (thus it excludes audio files, videos, etc.). First, it is explained how knowledge residing in physical and virtual sources can be labeled. Based on the technique used to label this type of knowledge source, it is explained how tacit knowledge residing in the minds of people can be labeled.

Chapter 6.2.1: Labeling of Knowledge Residing in Physical and Virtual Objects

Unstructured information in the form of natural language text is an important source of information in organizations (Uys, Uys et al. 2008). Unstructured information is found in both physical and virtual objects such as books, reports, text messages, web pages, e-mails, word processor and other computer files, and many more (Uys, Du Preez et al. 2008). This unstructured information is only useful to an organization when its content can be automatically and electronically interpreted, grouped, and understood (Uys, Du Preez et al. 2010). Thus, physical objects must first be digitized in order to be electronically interpreted and to be of use to an organization. However, determining what a (set of) document(s) is about is not an easy task; traditional approaches such as analyzing documents and manually categorizing them are very time-consuming an labor intensive, and tools such as text summarization tools are largely ineffective (Uys, Du Preez et al. 2008). In addition, these difficulties are amplified when there is a large number of documents available and/or the locations of documents are distributed (Uys, Uys et al. 2008). According to Uys et al., three types of technologies can be helpful when working with large collections of natural language text. These technologies are information retrieval technologies/full-text searching software, clustering/classification technologies, and Natural Language Processing (NLP), data mining and visualization technologies (Uys, Du Preez et al. 2008). Firstly, information retrieval technologies or full-text searching software provide documents based on a user's search query. The user types in a search query and the technology returns ranked sets of matching documents (Uys, Du Preez et al. 2008, Uys, Uys et al. 2008). This approach has several shortcomings, such as misspellings and different terminology that can lead to poor results (Uys, Uys et al. 2008). Moreover, this type of technology does not provide users with an overview of underlying concepts in a document collection (Uys, Du Preez et al. 2008). Secondly, clustering/classification technologies are mostly used to organize and group documents of a document collection (also named document *corpus*) based on their content (Uys, Du Preez et al. 2008). Clustering can be defined as "the process of organizing things without the need to provide predefined categories" (Uys, Du Preez et al. 2010). With clustering, the categories are derived from the processed data. Contrasting to clustering, classification can be defined as "the process of organizing things using predefined categories" (Uys, Du Preez et al. 2010). After clustering or classifying documents based on their content, some technologies further provide a characterization of the topics contained in the document collection. Lastly, Natural language processing (NLP) can be used to discover knowledge by extracting interesting information from document collections (Uys, Du Preez et al. 2008). Natural language processing techniques can be divided into two categories: techniques regarding entity mining and techniques regarding mining of relations (Uys, Uys et al. 2008). With entity mining techniques, single-word entities are mined from electronic document text, and a list of occurring words plus their frequency of occurrence is generated (Uys, Uys et al. 2008). Uys et al. state that "as a rough approximation, words whose frequency falls within the 80th percentile can be viewed as the most relevant single-word terms in the given document". Other techniques may subsequently be used to group closely related words and to get an idea of unique single-word concepts covered in the natural language text (Uys, Uys et al. 2008). Techniques regarding mining of relations deal with the mining of relations between entities in natural language documents (Uys, Uys et al. 2008). Relations between entities may be found by searching for a subject and object for (pre-selected) verbs in the text (Uys, Uys et al. 2008). Mining of relations is more difficult than entity mining and is therefore less mature. The technologies that are mentioned each have their own advantages and disadvantages; however, clustering/classification technologies are the only type of technology that extracts topics from a document collection, and thereby creates a feeling of its content. Therefore the use of topic models is recommended by Uys et al. (Uys, Du Preez et al. 2010) to extract the essence from a document corpus. Topic models are a form of clustering/classification technology that can be used to process large collections of textual documents (Uys, Du Preez et al. 2008). A short description of the topic modelling process based on the LDA approach (M. Blei, Y. Ng et al. 2003) is given based on the paper by Uys et al. (Uys, Du Preez et al. 2008). Topic models extract a certain number of topics (as specified by the user) that are covered in a document corpus. By means of a topic-word matrix, the words that are associated with each topic are presented. In analyzing the topic-word matrix, the user can get an overview of the topics that are covered in a document corpus, without actually reading the documents. On inspection of the calculated topics, each topic may be given a descriptive label by the analyst by evaluating the words and terms allocated to the specific topic. A second matrix, which is the document-topic matrix, subsequently provides the likely allocations of documents to the calculated topics. By analyzing this matrix, one cannot only assess which topics are well represented by the document corpus and which are not, but one can also find out which documents significantly describe which topic(s) by analyzing the mixing ratios of individual documents. The mixing ratio of a document is based on the occurrences of words (as given by the topic-word matrix) per document. In addition to analyzing a (large) document corpus, one can also run a subset of documents corresponding to a certain topic or analyze a single document. In conclusion, a topic model associates documents with topics. The topic-word matrix together with the document-topic matrix provides a useful mechanism to explore a document collection on a higher level. By using a topic model, topics that are covered in a document corpus can be extracted and matched with documents that describe these topics with the highest probability (as can be seen from the mixing ratio). In this way, information and potential (tacit) knowledge can be found more efficiently and effectively.

Chapter 6.2.2: Labeling of Knowledge Residing in People

In order to label knowledge that resides in the minds of people, several things can be done. Firstly, an organization could use a tool similar to Philips' Yellow Pages. Philips' Yellow Pages is an intranet-based tool that lists experts with different kinds of knowledge they have stated to have. A user types in the keywords for a specific knowledge domain and the system retrieves a list of people within Philips who have stated to have the knowledge in question. One of the advantages of this system is that it includes organizational members of Philips from all over the world, and in this way connects experts and people searching for knowledge on a global scale. However, this type of system has some significant disadvantages. Not only is personal knowledge prone to change and thus requires frequent (manual) updating of the system, it also only stores that knowledge that people consciously know they have. This excludes a lot of tacit knowledge that people do have, but that they are not aware of. Thus, this type of system cannot be used to label tacit knowledge. Secondly, knowledge can be labeled based on the visual effects or consequences it entails. As explained in chapter 5.4, the effects/consequences of having certain tacit knowledge can be observed. Visible effects of tacit knowledge are for example expertise, roles assigned in specific projects, or even an assigned function or department. However, indicating who possesses what tacit knowledge based solely on these terms is simply guessing and is very open to interpretation. Nonetheless, the visual effects of having tacit knowledge can be used in conjunction with another option that is described now. A third option is to create 'information profiles' (Uys, Du Preez et al. 2010) for individuals based on the topic modeling approach explained in chapter 6.2.1. Information profiles can be used to obtain an idea of what knowledge and expertise an individual possesses (Uys, Du Preez et al. 2010). More importantly, information profiles provide a visual representation of (tacit) knowledge individuals possess. Uys et al. explain that individual information profiles can be created (and updated) automatically by firstly identifying which documents are authored or read by an individual in a given time period, and then using these individual document sets to create a topic model for each of these sets. See figure 38. Each topic model then suggests the likely topics an individual has interacted with, and possibly has (tacit) knowledge of. By using this mechanism, relationships between knowledge areas and individuals can be established, and objective indications of the knowledge an individual possesses can be estimated (Uys, Du Preez et al. 2010). In addition, connections between people can be made, either between people with common knowledge areas (e.g. for exchanging (potentially relevant) documents) or between a person who has knowledge of a certain knowledge area and a person searching for specific knowledge. Moreover, organizational members can get an overview of which knowledge areas their organization deals with, and an organization itself can get an overview of which knowledge areas it is acquainted with.

The use of individual information profiles has some additional (organizational) advantages. Firstly, information profiles promote communication and transfer of tacit (and explicit) knowledge within an organization by triggering (face-to-face) interaction. Information profiles can identify and suggest connections between organizational members and facilitate the transfer of (tacit) knowledge of topics they have in common, or of topics one requires knowledge of. Secondly, by using information profiles, people and their knowledge/expertise can be managed in a better way. When an organization knows which knowledge is possessed by which individual, individuals can be assigned to projects that require specific knowledge. In this way, information profiles can assist in identifying which individuals should be involved in which projects/processes and, accordingly, knowledge and expertise of organizational members can be used in a more optimal way. Thirdly, information profiles (but also topic models in general) can contribute to more informed and speedy decisions. By providing information of where knowledge can be found (being either an individual (through information profiles) or an object (through topic modeling)), the process of decision-making is facilitated. Lastly, information profiles can enable the capturing of social networks and relationships within an organization by analyzing the connections between organizational members.

It must be noted that, although individual information profiles can be automatically created and updated by the system, it is advised to enable users to edit their own information profiles. By enabling this interaction, individuals can remove topics that they are not acquainted with, or add topics that they know they have knowledge of. In this way, accuracy and relevance of information profiles is increased.

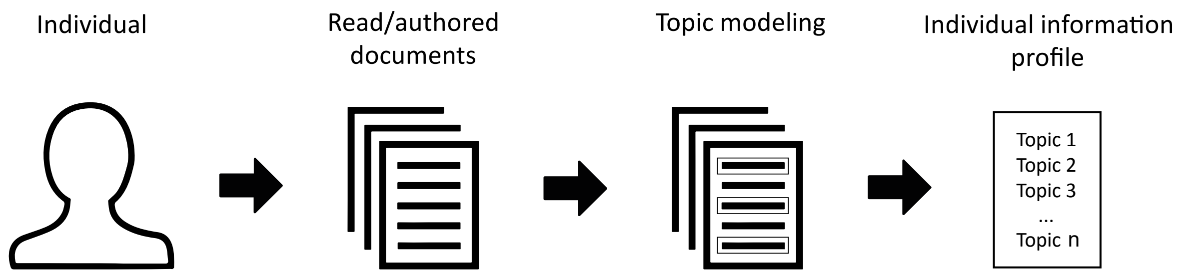


Figure 38: Creation of individual information profiles

Chapter 6.3: Obtaining Tacit Knowledge

The goal of this thesis is to design a system that provides designers with relevant information during all stages of product development. Whether information is relevant can only be determined by the user of the system, i.e. the person that is searching for information or knowledge. Consequently, the system cannot determine whether information is relevant to a certain person. However, the system can aim to provide information that has a high chance of being relevant based on, for example, search queries performed by the user and his/her previous interactions with certain knowledge areas.

There are two ways in which information can flow from the system to the user: by means of information pull and by means of information push. Two definitions are given by Hermans (Hermans 1998) that clearly describe the difference between the two concepts:

"Information pull is where a consumer or user takes (or is given) the initiative to get it"
"Information push is where a supplier takes (or is given) the initiative to deliver it"

In other words, one can obtain information by actively searching for it, or by having it delivered without effort. Examples of information pull technology are web browsers and FTP; examples of information push technology are mailing lists and unsolicited e-mail (Hermans 1998). Many applications of push and pull technology can be found in, for example, information databases and web shops. ScienceDirect, a platform for peer-reviewed literature, uses push technology to push journals, articles, and book chapters that have been read by other users, based on a search query performed by a user. In this way the system returns documents that are relevant to the search query and, when the user downloads a certain document, also pushes additional documents that have been read by people that have also read the document in question. Although this might seem convenient, the pushed documents are not necessarily related or relevant to the document that has been downloaded; they are not recommended based on the topic(s) or context they cover, but they are only recommended because they have been read by the same people that have also read the document in question. This principle is also applied to many web shops. Web shops such as H&M push products based on individual browsing behavior and viewing history, often accompanied by sentences such as "You may also find this interesting" or "Other people also bought". To keep customers engaged, some web shops also push products via e-mail that are saved to wish lists or are kept in online shopping bags. Although this type of push technology used by web shops attaches less value to providing relevant information, it still tries to push products that might be interesting to the user. Is it therefore not more logical to push information that is similar to that information one is looking for, instead of pushing documents or products that are viewed or bought by other people?

The system that is designed in this thesis also uses the principles of information pull and information push. How the system employs these principles is explained now. The system employs information pull in a relatively easy and standard way. A user enters a search query (or search *term*) and the system provides information matching that search query by pulling it from the knowledge base. This information i.e. the result of a search query can be two things: specific information instantiations that cover the topic sought after and specific information profiles of people that have been in touch with the knowledge area that is sought after. Objects are used as the source of knowledge by matching information instantiations to query strings; people are used as the source of knowledge by matching information profiles to query strings. Tacit knowledge can be obtained by analyzing the document in question (e.g. by drawing conclusions that are not explicitly formulated in the document) or by consulting the person whose information profile is provided. Depending on the type of knowledge that is sought (when specific competences are sought, it is more logical and useful to obtain an information profile of the person that possesses that (tacit) knowledge), an organization might choose to incorporate one or the other, or both. In addition, information can be pulled from the knowledge base by creating individual information requirement profiles. Uys et al. mention that "individuals can set up information requirement profiles that can be used to automatically generate individual notifications when certain kinds of information become available in the knowledge base" (Uys, Du Preez et al. 2008). In other words, using predefined information needs as set up by individuals, automatic notifications regarding matching information can be send to those individuals that are in need of specific knowledge. This matching information can come from newly available documents in the knowledge base containing a certain topic (as determined by the topic modeling approach) or from updated information profiles (in this case the matching information refers to a person having that information or knowledge).

To push/recommend information to the user, three options are identified. The first option is to push information instantiations with a high mixing ratio for a similar topic, based on a search query performed by the user. This option uses the topic modeling approach based on LDA as is described in chapter 6.2.1. Uys et al. explain that "with LDA, the similarity of a given document to other documents can be estimated by identifying other documents that were allocated to the same topic as the given document with high mixing ratios" (Uys, Du Preez et al. 2008). In other words, documents related to a certain topic – and therefore related to each other – can be found by examining the document-topic matrix to determine which documents have the highest mixing ratio for a certain topic. When a user enters a search query and interacts with a certain document, information instantiations covering similar topics can be pushed to the user. This is very similar to the information push concept used by information databases such as ScienceDirect, but the system that is designed here pushes documents with similar topics rather than pushing documents that have been read by the same people. A similar option is to push information instantiations based on inter-document relation extraction. In contrast to intra-document relation extraction which is described in chapter 6.2.1 under the natural language processing technique, inter-document relation extraction deals with the identification of relations between documents based on their content (Uys, Uys et al. 2008). This approach is similar to the topic modeling approach described in the first option, although the inter-document relation extraction approach described by Uys et al. uses LSA instead of LDA (Uys, Uys et al. 2008). LSA, or latent semantic analysis, can be used to obtain relations between different concepts, and between documents and concepts. Using LSA, the relatedness of documents can be estimated based on the conceptual similarity of the content of the different documents (Uys, Uys et al. 2008). Documents with a high conceptual similarity can be pushed to a user based on documents one has already found relevant or interesting (because the user has interacted with it), or because a user is in need of more information or knowledge similar to that relevant content. A decision between both options can be made based on the preferred technique (LDA or LSA respectively). The second option is to push information profiles of people with similar or related knowledge to the topics covered in a document. In this way, people and the (tacit) knowledge they possess are directly linked to topics covered in documents and provided to the person that is searching for knowledge. The third option is to push information instantiations based on individual information profiles. As described in chapter 6.2.2, individual information profiles can be used to get an idea of what knowledge and expertise an individual possesses, based on topic models of documents an individual has interacted with in a given time period. Based on individual information profiles and knowledge areas represented in these profiles, information instantiations covering similar topics to those topics mentioned in an information profile can be pushed to the user. For instance, when a user has knowledge of topic X as reflected by his/her information profile, the system can push information instantiations covering topic X or topics similar to topic X (based on its context). In this way, an individual can obtain information instantiations that are relevant to his/her knowledge area or interests.

The options that are mentioned (summarized in figure 39) can all be combined or any combination of one or more options can be made. The use of information profiles and information requirement profiles ensures that the right information is available to the right people and can be obtained at the right time.

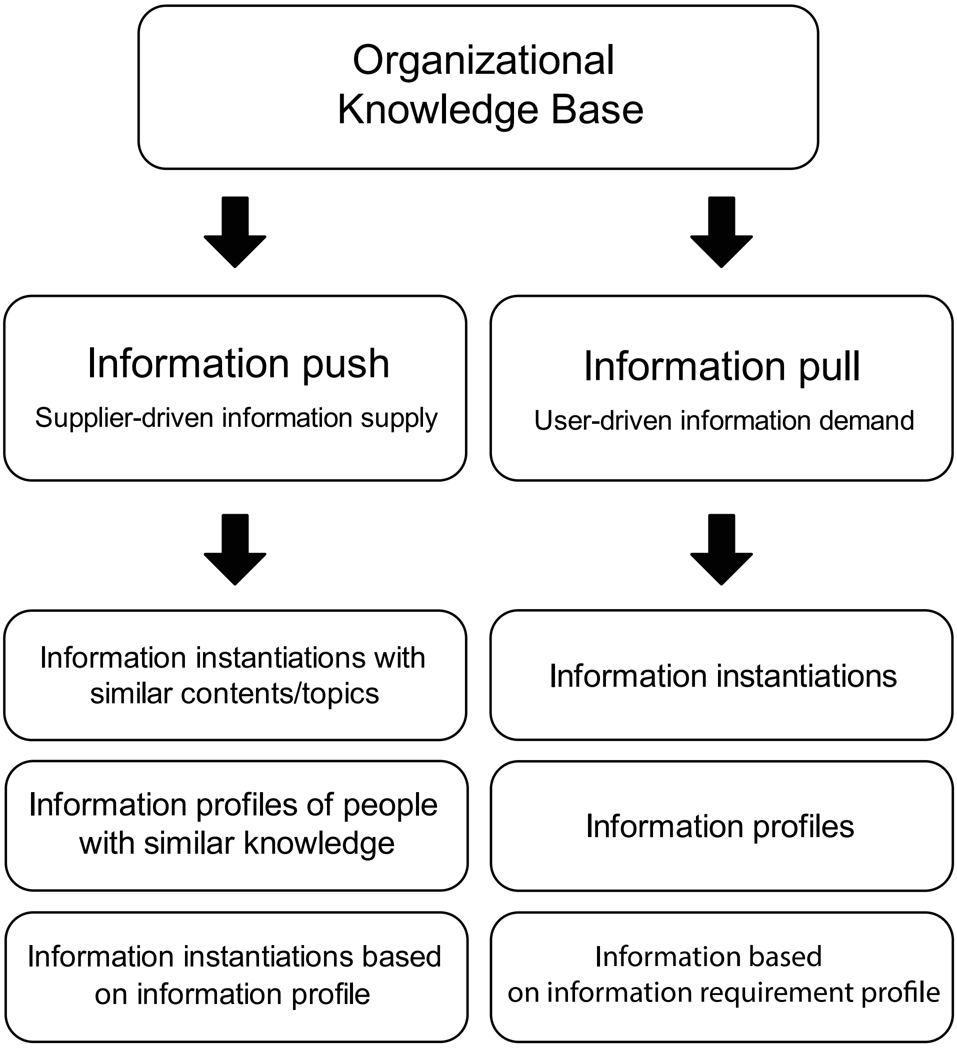


Figure 39: Information obtained through information push and information pull

Chapter 6.4: User Interactions

Before information can be pulled from the system by the user, or pushed to the user by the system, this information must first be created and made available to users. The proposed system manages knowledge by connecting knowledge sources and providing information about these knowledge sources. As explained, these knowledge sources can be physical and virtual objects (in the form of information artifacts, see chapter 6.2.1) and individuals that possess knowledge (see chapter 6.2.2). Firstly, knowledge sources in the form of artifacts (created or read by organizational members) are entered into the system manually by individuals that interact with these documents. Subsequently, these information artifacts become part of a network of documents that connects documents describing similar topics. This network of documents expands as more documents are entered and/or created in(to) the system, and smaller networks within this larger network are created through the topic modeling technique. Figure 40 provides an example of a simplified network of interrelated documents and topics (here called a *topic-document network*). The white nodes represent specific topics that are calculated through the topic modeling technique. These nodes connect single information artifacts based on their mixing ratios for specific topics. The black nodes represent the information artifacts that cover these topics. As can be seen from figure 40, one topic can be described by multiple information artifacts, and one information artifact can describe multiple topics. It can be chosen to include all topics that are covered by an information artifact, or it can be chosen to select only those topics that are best represented by the given information artifact. Which topic is best represented can be determined by analyzing the mixing ratios of a specific document for the calculated topics; the topic that has been assigned the highest mixing ratio is best represented by the document in question.

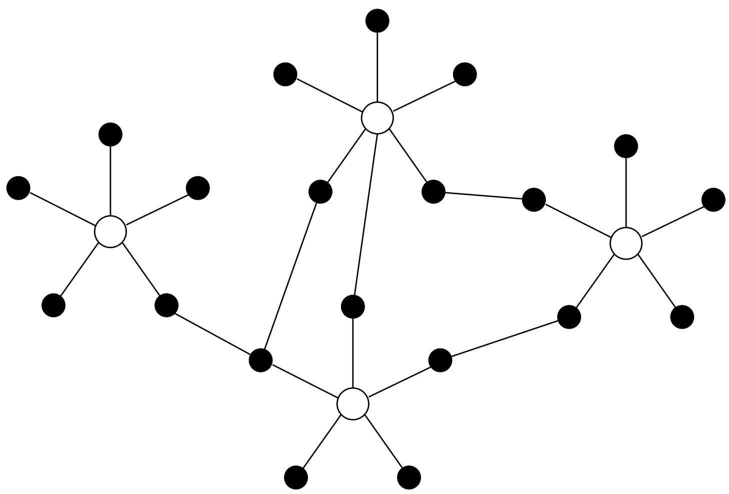


Figure 40: An example of a basic topic-document network

As mentioned, information artifacts must either be created in the system or must be entered into the system by organizational members. It is assumed that all information/knowledge that is sought by individuals is actually available in the system because it is created or entered on beforehand. If the exact keywords that are used in a search query provide no (desired) results, the system can provide alternatives based on synonymy. As explained by Uys et al., topic models are well-suited to cater for synonymy (and also polysemy), as topic models assign words to topics based on the context of the document (Uys, Du Preez et al. 2008). To achieve this functionality, a precondition is that there is a large number of information artifacts available in an organization. Moreover, the information artifacts that are available must contain enough natural language text to enable analysis (i.e. topic extraction) by the topic model.

Secondly, knowledge sources in the form of people are made available through the creation of information profiles (see figure 38 on p.74). To create individual information profiles, it must be tracked who has authored/interacted with which documents in a given time period. This can be done by, for example, using the transaction logs of a document management system (Uys, Du Preez et al. 2010). Based on this information and the topic modeling technique, personal topic-document networks can be created that serve as input for the individual information profiles. Consequently, these personal topic-document networks can be used to make connections between people based on topics they have interacted with. Furthermore, the creation (and updating) of information profiles based on personal topic-document networks is an automatic process that requires minimal to no attention from users. For more information about information profiles see chapter 6.2.2.

As explained in chapter 6.3, information/knowledge is made accessible to the user by means of information pull and information push. Information is pulled from the system by the user by setting up an information requirement profile or by using search queries with keywords. In case of information requirement profiles, information instantiations covering specific topics or information profiles of people that have interacted with specific topics/knowledge areas can be obtained by users based on the topics specified in their information requirement profiles. In case of information pull through search queries, information (being information instantiations or information profiles) is obtained by entering keywords into the system. See figure 41. To search for topics in a document collection, a precondition is that the topics calculated by the topic modeling technique have been assigned a descriptive label to 'name' the topic. However, this does not mean that one has to type in the exact word(s) that name(s) the topic: because specific words have been assigned to the topic by the topic model, one can also use these words in a search query (in this case, relevance of the obtained topic(s) must be determined). As can be seen from figure 39 on p.77, two types of knowledge sources can be pulled from the system by the user: information instantiations (i.e. objects that cover knowledge) and information profiles (i.e. people that possess knowledge). In order to pull information from the system, the user must select the type of knowledge source he/she wants to retrieve from the system. See figure 42. By selecting "information instantiations", the user will only retrieve information instantiations from the system as depicted in figure 43. Because the knowledge that is obtained through information artifacts is written/articulated in documents, it is by definition articulatable/expressible knowledge (note that tacit knowledge can be obtained through information artifacts by drawing conclusions from explicit knowledge!). Therefore, this option suffices when the user is searching for more practical types of knowledge such as conceptual and systemic knowledge. However, when the user is searching for knowledge gained through experience such as experiential and routine knowledge, the user might want to select "information profiles" to get in touch with people that have interacted with (and possibly have knowledge of) specific knowledge areas. See figures 46 and 47. Keywords used in search queries are matched to the topics found in individual information profiles, and in this way the user gets access to tacit knowledge directly from the source.

In contrast to information that is pulled from the system by the user, information can also be pushed to the user by the system. Information push is initiated by human (inter)action and starts when the user enters a search query. Then, for information to be pushed to the user, the user must interact with a document. Interaction at least requires opening the document. When the user interacts with a certain document, the system pushes documents to the user that describe similar and/or related topics to the document in question. See figure 44. Which documents are pushed to the user depends on the documents that are present in the specific topic-document network. If there is a large number of documents present in the specific topic-document network, it is advised to push only those documents with the highest mixing ratios in relation to the given document. Moreover, to avoid the feeling of information overload, a specific number or maximum can be defined to the number of documents that are pushed to the user. In addition, active archiving of information instantiations with a low mixing ratio may help with reducing the feeling of information overload. In addition to pushing information artifacts, it is possible to push information profiles of people who have interacted with topics similar to topics described in a given document. This is depicted in figure 45. By tracking who has interacted with/authored which documents and subsequently using topic modeling to determine the topics covered in these documents, it becomes possible to create personal topic-document networks. When the specific document and the topic(s) it covers are located within this network and there is more than one node connected to these topics (the given document plus other document(s)), it can be said that this person has interacted with topics similar/related to the topics described in the document in question. By pushing information profiles, it becomes possible to consult people regarding a specific knowledge area, especially when information instantiations do not provide the knowledge the user is searching for. Lastly, information instantiations can be pushed to users based on their (automatically created) information profiles. In this case, potentially relevant or interesting documents can be pushed to users based on the topics found in their individual information profiles. Of course, this must also be limited to a certain amount to avoid the feeling of information overload.

Figure 41: Entering a search query (artist's impression of an interface)

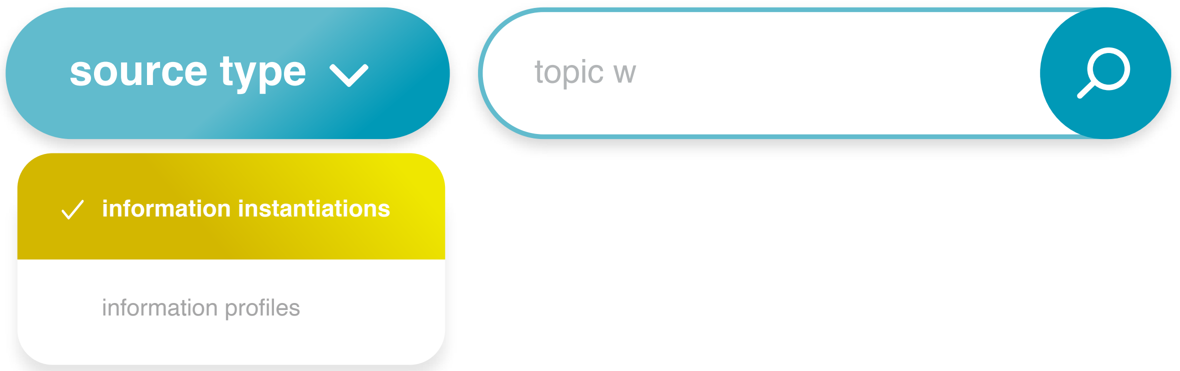


Figure 42: Pull of information instantiations (artist's impression of an interface)

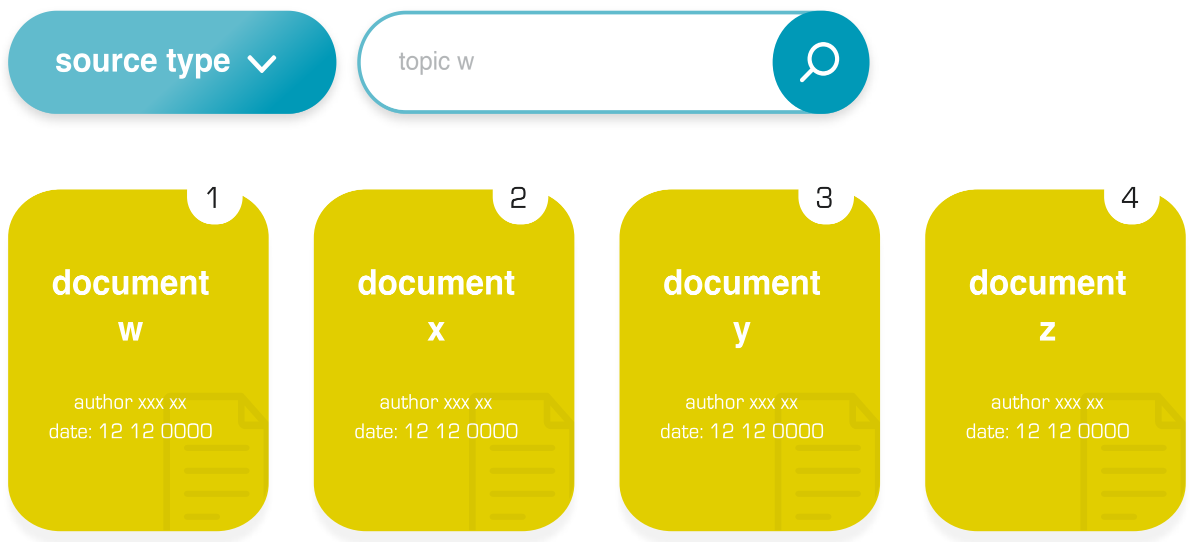


Figure 43: Retrieved information instantiations (artist's impression of an interface)

Figure 44: Push of information instantiations (artist's impression of an interface)

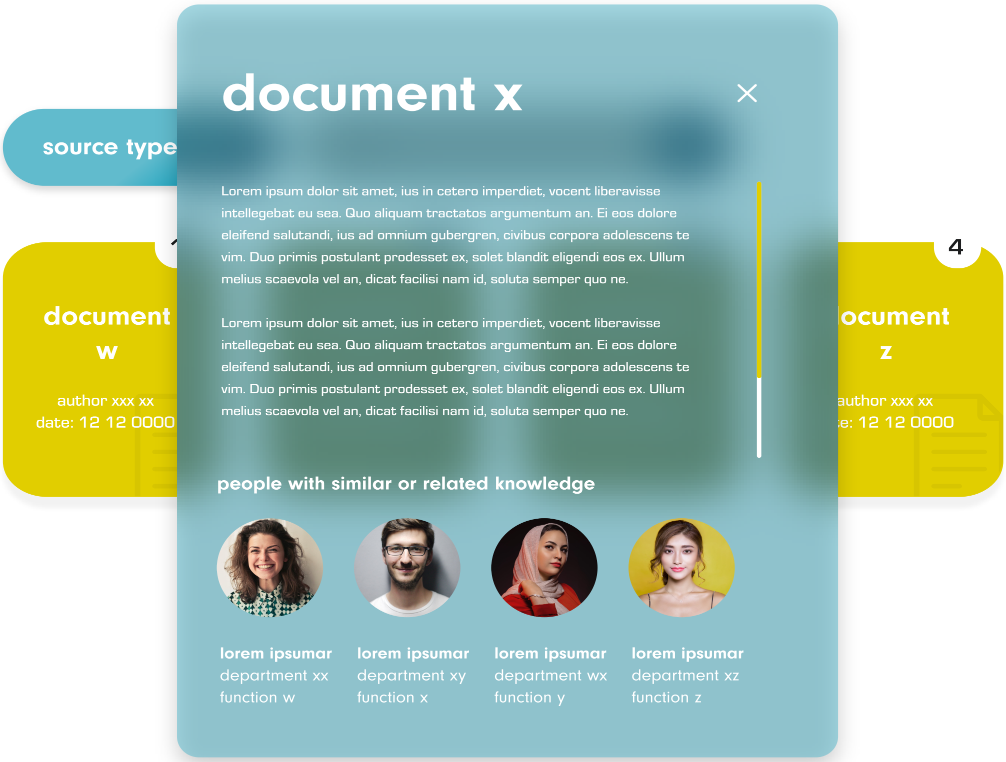


Figure 45: Push of information profiles (artist's impression of an interface)

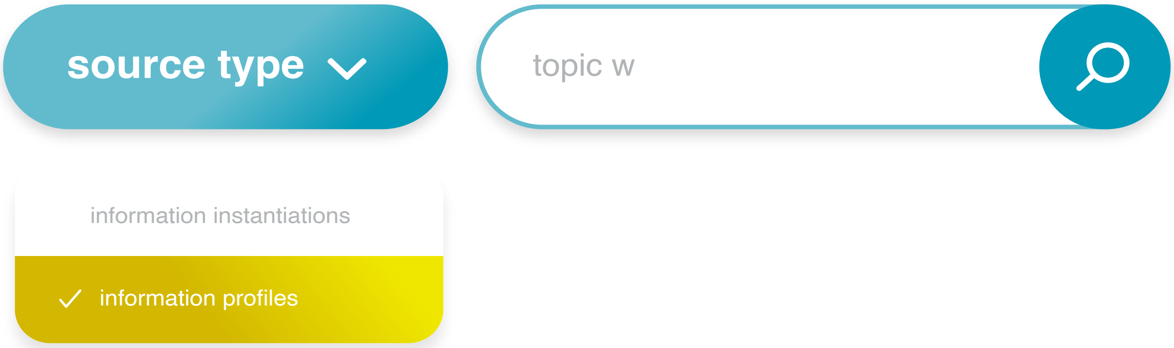


Figure 46: Pull of information profiles (artist's impression of an interface)

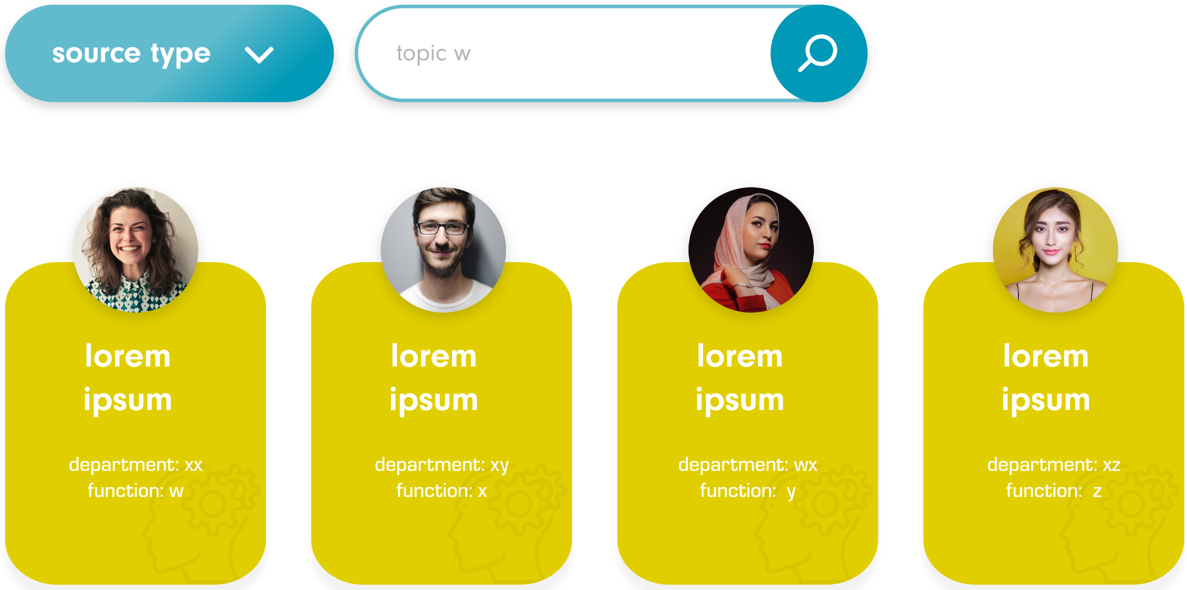


Figure 47: Retrieved information profiles (artist's impression of an interface)

Chapter 6.5: User Scenarios

Background

Organization X[10] is a small-sized enterprise with around 15 employees that designs and produces products in industry Y. Organization X operates from multiple locations and thus deals with a distributed workforce. Because organization X is a small-sized enterprise[11], knowledge sharing and mapping is not necessarily obstructed by the number of organizational members (which might be the case for medium-sized enterprises[11]), instead it is made difficult due to the fact that organization X operates from multiple locations. Because of its distributed workforce, organizational members might not be aware of the knowledge that is possessed by individuals that are not in their direct proximity.

Scenario 1 – Information pull

Roger is employed by organization X. Roger and a few of his colleagues are working on a special project, which we will call project Z, that has been initiated by organization X. Project Z is an innovative project that is different from any of the projects that have been executed by organization X. Moreover, this project targets a different industry and audience than the projects previously executed by organization X. Thus, Roger and his colleagues will need tacit and explicit knowledge to come up with the best solution, as they cannot rely on their own past experiences.

Project Z regards the creation of a children's toy that functions as a wake-up light, Bluetooth speaker, night light, and sleep trainer[12]. To get an idea about the (needs and desires of the) target group he is designing for, Roger needs knowledge about, for example, children's sleeping behavior and patterns, but also about how children interact with such toys and which effects it has on them. Because this subject has never been covered in projects executed by organization X, Roger decides to use mainstream search engines on the Internet and library repositories to collect documents that might contain relevant knowledge about children's sleeping behavior and sleeping patterns. After some searching on the Internet, Roger has found relevant explicit knowledge in several documents. He decides to download these documents and enters them in the knowledge management system of organization X for possible future reuse. In addition to explicit knowledge, Roger is interested in the experiences of people who have created similar toys or who have knowledge of the specific knowledge area. Thus, he enters the knowledge management system, selects 'information profiles' and types in the keywords 'children's sleeping toy'. Based on this search query, an information profile pops up. Roger decides to contact this person (lets name him Bob) through the information provided by the information profile. After asking Bob some questions, Roger finds out that, although Bob has never been involved in the creation of a children's sleeping toy, Bob has actually been involved in other projects that involved children. Roger explains the project he is working on and Bob provides him with valuable explicit knowledge and tacit knowledge that he has gained through his experience with similar projects. After talking to Bob, Roger realizes that, although the subject of children's sleeping toys has never been covered by organization X, he can still use the knowledge management system to search for documents that cover similar topics. He switches to the option 'information instantiations', types in several keywords such as 'children's sleeping toys', 'children's toys', and 'children', and retrieves some documents that cover these topics. Roger reads the documents and obtains explicit and tacit knowledge that is relevant to the project he is working on. Because of his

[10] Organization X is based on an existing small-sized organization that operates in industry Y.

[11] The European commission has defined a small-sized enterprise as an enterprise with a staff headcount of less than 50 and an annual turnover of less than €10MM. For medium-sized enterprises, this is a staff headcount of less than 250 and an annual turnover of less than €50MM.

[12] Based on an existing sleeping toy created by organization X.

interaction with these documents, the system updates his individual information profile with the topics covered by the documents in question. Although the knowledge Roger has obtained through the retrieved documents is relevant and valuable, it is not enough to solve all of the questions he is dealing with in this innovative project. Therefore, Roger decides to create a personal information requirement profile in which he defines the topics he needs more knowledge about. He enters several keywords such as 'children's sleeping toys' and 'sleeping toys effects'. Based on his information requirement profile, Roger will get a notification when knowledge regarding the specified topics becomes available in either the knowledge base or when it is defined in (updated) information profiles of organizational members. In the meantime, Roger continues his research into the chosen target group. With the experiential knowledge Roger has obtained from Bob and the knowledge he has obtained through the documents he has interacted with, Roger has enriched his personal knowledge base. To be valuable for organization X, this knowledge must be managed and shared with other organizational members through face-to-face interaction or through the knowledge management system to form a new spiral of knowledge creation.

Scenario 2 – Information push

Amy is a colleague of Roger and Bob has been working together with Roger on project Z. Amy is a product designer and has been given the task to come up with some designs for the children's sleeping toy. Because Amy has never designed a similar product for the given target audience, she requires knowledge to create a good design. To obtain this knowledge, Amy enters the knowledge management system. Because she is unsure what specific knowledge she needs, she starts searching for knowledge intuitively. Amy selects the option 'information instantiations' and starts her search query by entering keywords into the system from which she thinks they might be relevant. She enters general keywords such as 'toy design' and 'toy features' to obtain a wide range of topics. After some searching, she has found a document that she believes contains knowledge that will help her with designing the sleeping toy. Amy opens the document and starts reading the text. By reading the text and drawing conclusions, Amy obtains new tacit (and explicit) knowledge that can help her with her design. When she finishes reading the text in the document, she notices that the system has recommended several other documents that describe similar topics. Because Amy has interacted with the document in question, the system has pushed additional documents to Amy that have a high mixing ratio for the same topics in relation to the document she has interacted with. The documents that have been pushed to Amy by the system capture her attention and she decides to take a look at some of the recommended documents. She opens one of the documents and starts reading. When she finishes reading the document Amy has obtained new knowledge, but she is left with some questions regarding the topics covered in the document. The document in question is not authored by a member of organization X, so she cannot contact this person. However, she notices that an information profile has been recommended of someone who has similar knowledge in relation to the topics in the document in question. This information profile has been pushed to Amy based on the topics covered in the document. She decides to contact this person to find out whether this person can help her. After a short conversation, Amy concludes that this person indeed has knowledge of the topics in question as well as knowledge of related topics. More importantly, Amy has obtained the answers to her questions. With the knowledge obtained, she is able to continue her process of designing the sleeping toy. Moreover, the topics that are described in the documents that Amy has interacted with are added to her individual information profile. In the future, this information profile can be used to push documents to Amy, based on the knowledge areas she has interacted with. Her (updated) information profile can also be pushed to other people as a source of knowledge, and in this way start off a new knowledge creation spiral that disseminates knowledge throughout organization X.

Chapter 6.5: Conclusion

This chapter has described the functionality of the black box model that is proposed in chapter 5.5. Through information push and pull, users are provided with potentially relevant (tacit) knowledge. Topic modeling enables the extraction of topics from natural language text documents and enables the creation of individual information profiles. Consequently, natural language text documents can be compared, and relevance can be determined by analyzing topics and mixing ratios. In addition, individual information profiles enable the allocation of (tacit) knowledge to organizational members. In this way, objects serving as knowledge sources can be labeled by extracting the topics they cover and listing these topics for each natural language text document; people serving as knowledge sources can be labeled by listing the topics/knowledge areas they have interacted with in individual information profiles.

As mentioned throughout this thesis, tacit knowledge is very hard to impossible to manage without making it explicit. This chapter has proposed a model that manages tacit knowledge without having to articulate it. As explained in this thesis, there are advantages and disadvantages to leaving tacit knowledge in its intangible state. One major disadvantage is that tacit knowledge might leave an organization when employees leave an organization. This means that knowledge that is not articulated and thus remains tacit in the minds of people may disappear from an organization when individuals become incapacitated, retire, leave an organization, or are recruited by competitors. However, the disadvantages of trying to convert tacit knowledge into explicit knowledge are considered more important than the mentioned disadvantage. Moreover, because of the creation of information profiles, an organization can analyze which knowledge is present in an organization and which knowledge will disappear when people leave an organization. In this way, an organization can anticipate on the potential loss of knowledge and capabilities.

Chapter 7: Conclusions & Recommendations

Conclusions

The goal of this thesis was to design a system that provides users with relevant tacit knowledge. To accomplish this goal, this thesis has proposed a black box system for the management of tacit knowledge. This black box system uses explicit knowledge to provide the user with an idea of where potentially relevant tacit knowledge might be found. Tacit knowledge that resides in physical and virtual objects is managed through the topic modeling approach as explained in chapter 6. This is an automatic process that requires no to minimal effort from an organization's employees. Potentially relevant objects can be provided to users based on their information (requirement) profile or pulled from the system by the user based on search queries. Tacit knowledge that resides in people is managed by information profiles created through the topic modeling approach. Individual information profiles are automatically created and updated by the system based on information instantiations individuals have interacted with (in a given time period), and therefore requires no attention from organizational members (it is not labor-intensive because employees do not need to update their information profiles manually). Individual information profiles can be pulled by/pushed to users as a source of (tacit) knowledge or can be provided based on information requirement profiles. By managing tacit (and explicit) knowledge (e.g. by pushing potentially relevant knowledge based on topics) in a more efficient and effective way, the proposed black box model facilitates quicker and better decision-making and problem solving and overall improves product development activities.

The major benefit of the proposed system is that is manages tacit knowledge without having to make it explicit. In this way, it taps into the tacit knowledge base of organizational members. Although many organizations try to articulate tacit knowledge of their personnel and manage it as explicit knowledge, this system locates the sources of tacit knowledge and manages these sources instead of the (unarticulatable) knowledge itself. In this way, tacit knowledge preserves its intrinsic meaning and value as it is not separated from its source. Thus, highly personal and context-related knowledge can be managed in a very valuable tacit form. This thesis has provided the methodology and method to create such a system for the management of tacit knowledge. The proposed system consists of a black box model and theoretical underpinning of how information is provided through this black box model by using the principles of information push and information pull. With the methodology and method provided by this thesis, the proposed system for the management of tacit knowledge can be realized. In order to realize this system, the only additional element needed is the technology (i.e. software) to realize the functionality of the system. This thesis has deliberately excluded the creation of a practical application from the scope in order to create a general, context-free solution for the management of tacit knowledge. By creating a black box system, the applicability and suitability of the solution are extended, as it is not limited to a specific context.

The proposed system can create value for an organization in several ways. One of the most important benefits of the system is that it enables reuse of information and knowledge and consequently stimulates the creation (and sharing) of new tacit and explicit knowledge. Subsequently, this knowledge can be used to make product development processes run more smoothly by facilitating processes such as decision-making and problem solving. As mentioned throughout this thesis, creating and managing (tacit) knowledge is the key to obtaining and maintaining competitive advantage. In addition, the proposed methodology and system stimulate a more efficient and consistent way of working by eliminating unnecessary activities and processes and by providing (potentially relevant) tacit and explicit knowledge throughout a product's life cycle.

Not only does the proposed system add value to the intended type of organization and industry, it can also be applied outside the scope of this thesis. As explained in this thesis, the system that is proposed is aimed at the development of physical consumer products created by discrete manufacturing industries. Although it is created for this industry, it is not limited to the discrete manufacturing industry. This means that the system may also be applied to, for example, the development of non-physical, intangible goods and services, or to the development of business/ capital goods. In all types of industry, information and knowledge are produced that must be managed and shared. For those industries that produce (either physical or non-physical) products, value is created by improving processes and products; for intangible goods such as natural resources processed by the process industry, value can be created by improving processes. In general, the proposed system can be of use to all development environments (and especially *distributed* product development environments) that involve (a certain amount of) information and people. This thesis has focused on small and medium-sized enterprises in the discrete manufacturing industry. It was chosen to focus on this type of enterprise because of the amount of information and knowledge that is present/available within the organization, and the tendency of the organization to continue on its current trajectory (i.e. *organizational inertia*). It is well known that, generally, large organizations are less responsive to change and sometimes they even resist change. This might be explained by the fact that many large organizations employ a process-based development model to guide product development activities. However, by following this process-based model (too) strictly, an organization might get stuck in a certain routine of activities that might work to produce products, but it might not necessarily produce the best products or produce them in the most efficient manner. Thus, although they meet the requirement of dealing with abundant information and (organizational) knowledge, change may not be achieved as easily as with smaller organizations. Therefore, for large organizations, the focus must be put on developing an information-based methodology. For start-ups, it is the other way around: although their product development activities are probably less fixed (because they have existed for a shorter time period) and they might therefore be more willing to change their processes and routines, the amount of information and knowledge that is available might not (yet) require the use of an information system. Therefore, for start-ups, the focus must be put on creating information and knowledge. Because of the reasons mentioned above, this thesis has focused on small and medium-sized enterprises, but as explained, it is not limited to this type of enterprise. In all environments (and especially those environments with distributed workforces), the system facilitates knowledge creation and dissemination, decision-making, and problem solving by providing potentially relevant tacit (and explicit) knowledge. However, it must be emphasized that the system is probably more likely to increase efficiency when the amount of people and the knowledge they possess is unclear due to the amount of people within an organization, and/or the amount of information within an organization is too large to be managed without an information system. In these environments, the system can play a pivotal role.

Recommendations

This thesis has addressed how tacit knowledge can be managed by an information system without having to make this knowledge explicit. A black box model has been provided for this purpose. The first, most logical step after this research is to create a practical application or prototype of the proposed system. In order to realize the proposed system, three groups of people must be involved and informed: the design team, the software developer, and the managing director. Firstly, a design team must be composed to design the system in terms of the user interface and user experience. Although this thesis has described the functionality of the system, no definitive design has been provided. When the front-end of the system has been designed, this team must (possibly in collaboration with an internal team) gather knowledge sources within an organization and provide an overview of these knowledge sources. This means that they have to provide (important) electronic documents, but also that they have to digitize important physical documents. If an organization already employs an information management system, this system can be used as a basis; if an organization employs multiple information management systems, the information present in these systems must be merged. In addition, the design team must provide an overview of organizational members and their department and function in order to enable the creation of information profiles. Moreover, it would be helpful if an overview is created of who has interacted with/authored which documents; this is so that the software developer can create and set up initial individual information profiles. Secondly, the tasks of the software developer are the following. One of the first things the software developer has to do is create the topic modeling software the system is running on. This does not require any information from the design team and can be executed independently from the tasks performed by the design team. Another task that he has to perform is setting up the back-end of the system and creating the user interface/front-end of the system that is designed by the design team. This part is very important for efficient and effective user interaction. Lastly, with the information artifacts the software developer receives from the design team, he is able to fill the database/back-end of the system with information instantiations and information profiles.

Once the proposed system has been realized, it must be marketed and made available to organizations. To achieve this, it is advised to market and sell the proposed system as a service, as implementation can be different for every organization (depending on e.g. the information management systems in use) and therefore must be individually tailored to each organization. Subsequently, the system must be implemented and tested within the organization. Previous literature and research have proven that topic modeling software can be successfully created and tested, but this does not mean that the implementation of the system within the organization should not be tested. To implement and test the proposed system, it is advised to start with a small group of people throughout the organization. Middle managers can be used as an important test group within an organization, because they serve as a bridge between top management and lower management. When the system has been implemented and tested, middle managers can be given the task to explain the functionality of the system and disseminate it to their division or department. Additional tools such as an instruction manual can be distributed throughout the organization to further clarify the goal and function of the system, or a seminar can be organized to explain this to organizational members through face-to-face communication. The organization in question can choose either one or a combination of the options mentioned above.

Lastly, to come back to the three groups of people that must be informed, the managing director is advised to start implementing the envisioned system into practice as soon as possible. The proposed system facilitates knowledge sharing of both explicit and tacit knowledge. It makes knowledge, and in particular the very important tacit variant, more accessible and usable, which is very important in making good decisions, solving problems, and obtaining and maintaining competitive advantage. Although it must be said that another model can be used (the model that is created is not definite and could have been different), there is, from a financial standpoint, no reason to not start implementing this knowledge management model or a similar model and I will explain why. Suppose that realizing and implementing the proposed system takes 2-3 months and costs around 10.000 euro. It is assumed that, for every significant project, a reduction of time and costs of approximately 10 percent can be realized. This means that, when dealing with a 100.000 euro project, the costs will be recovered within the first project, which makes it cost neutral. This also means that every project thereafter can be profitable. Again, this emphasizes that there is no reason not to implement the proposed knowledge management system and to take advantage of the benefits it offers.

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