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Educating the Guess: Strategies, Concepts and Tools for the Fuzzy Front End of Product Development

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Abstract- Many companies lack efficient management of the early phases of new product development (NPD) - the so-called fuzzy front end (FFE). Rather than on structured methods, decision makers rely on "gut –feel" or "guessing". In an attempt to "educate the guess" this paper discusses the activities and challenges of the FFE, as well as strategies to manage them successfully. It then briefly presents traditional and recent approaches to front-end management support. Based on the identified strengths and weaknesses of existing front-end solutions, the framework of a new management support system for the FFE is presented. Conceptually, the system is based on psychological findings about the process of action-regulation in complex decision environments. Methodologically, it uses Fuzzy Cognitive Maps (FCM) for modeling and simulation.

I   INTRODUCTION

The observation that pre-development activities strongly impact new product development performance and speed [e.g. 3, 4, 6] as well as innovativeness [22] has recently led to a growing interest in pre-development activities, sometimes referred to as the "fuzzy front end" of product development [19]. Researchers have investigated front-end practice in different industrial settings [19, 20, 32, 58] and have suggested approaches to improve front-end processes [6, 17, 19, 20,58]. Despite these efforts, many companies lack efficient front-end management and rely on "gut-feel" or "guessing" rather than on structured methods [32]. In an attempt to "educate the guess", this paper gives some structure to the challenges of front-end management and describes strategies and tools to meet them. Based on these findings, a new concept for decision support in the FFE is presented, which is methodically based on fuzzy cognitive maps.

II   FRONT-END MANAGEMENT: ACTIVITIES, CHALLENGES, STRATEGIES

A   Front-End Activities

According to Verganti early project phases are "the phases where the product concept is generated, the product specifications are defined and basic project decisions are taken, concerning the product architecture, the major components, the process technology and the project organization"[58, p. 377]. This view on the fuzzy front-end is largely undisputed among researchers: all front-end models contain similar activities, though they are sometimes termed differently and attributed to different stages of the front-end process [e.g. 17, p.80f; 20, p.59f; 22, p46ff; 30, p.143].

The outset of all front-end activities is a product idea - a potential, objectively and functionally described product [26, p.416], that seizes existing business opportunities such as unresolved customer problems, emerging markets, and unused technological potentials [17, P.82ff.]. Thus, the front-end bridges the gap between general strategic management activities (e.g. environmental scanning for product ideas or the planning of product portfolios) and project-specific product development tasks.

Further specification of the product idea leads to a product concept. Product concepts are mostly qualitative, verbal, pictorial or physical descriptions of a proposed new product. These descriptions deal with the customers that the product is targeted at, the functions it embodies, the needs it will satisfy, the product and process technologies it will be based on and the potential costs it will incur. If the new product does not create a market of its own, the description furthermore includes the product's advantages in comparison to competing products.

In the third and final phase of the fuzzy front end, product concepts are elaborated and complemented by first quantitative measures. The product concept is evaluated and tested with regard to its technological feasibility, its potential business success and its strategic fit [20, p.60]. Based on these evaluations, time, cost and volume estimates are made [17, p. 83]. Furthermore, the general product architecture is determined, i.e., the functions that are expected by the customer are specified and translated into main product components [35, p. 357ff; 54, p. 129ff]. If the product concept's technical or economical feasibility cannot be proven in this stage, product development is terminated before it entails high costs [3, 19,20]. If the product is considered to offer adequate profit potential at acceptable risk project plans (timeframe, objectives, contingencies) are decided upon [19, p. 110-112] and the product moves into the NPD execution stage.

It is important to note that the three fuzzy front-end phases are neither independent, nor completely sequential: frequently it will be necessary to reconsider strategic decisions (e.g. to adjust the product portfolio to the termination of a planned product) or to go back to earlier front-end phases (e.g. to modify a product concept that did not succeed in feasibility tests) [19, p. 108]. The interrelations with strategic planning and the interdependencies between different front-end activities and NPD-execution entail the major challenges of front-end management: uncertainty and interdependency. Both will be briefly discussed in the following section.

1) The challenge of uncertainty

Uncertainty is considered to be a key characteristic of the early phases of NPD. In the beginning of the front-end process, when the product idea is first generated, uncertainty is extremely high. Subsequently, it is reduced to a level that permits a "Go/No-Go" decision and the start of NPD execution [21, p. 269f].

In dynamic environments, however, uncertainty prevails throughout the entire NPD process, because environmental changes pose new questions and inflict new levels of uncertainty [31] (see line 2 in Fig. 1).
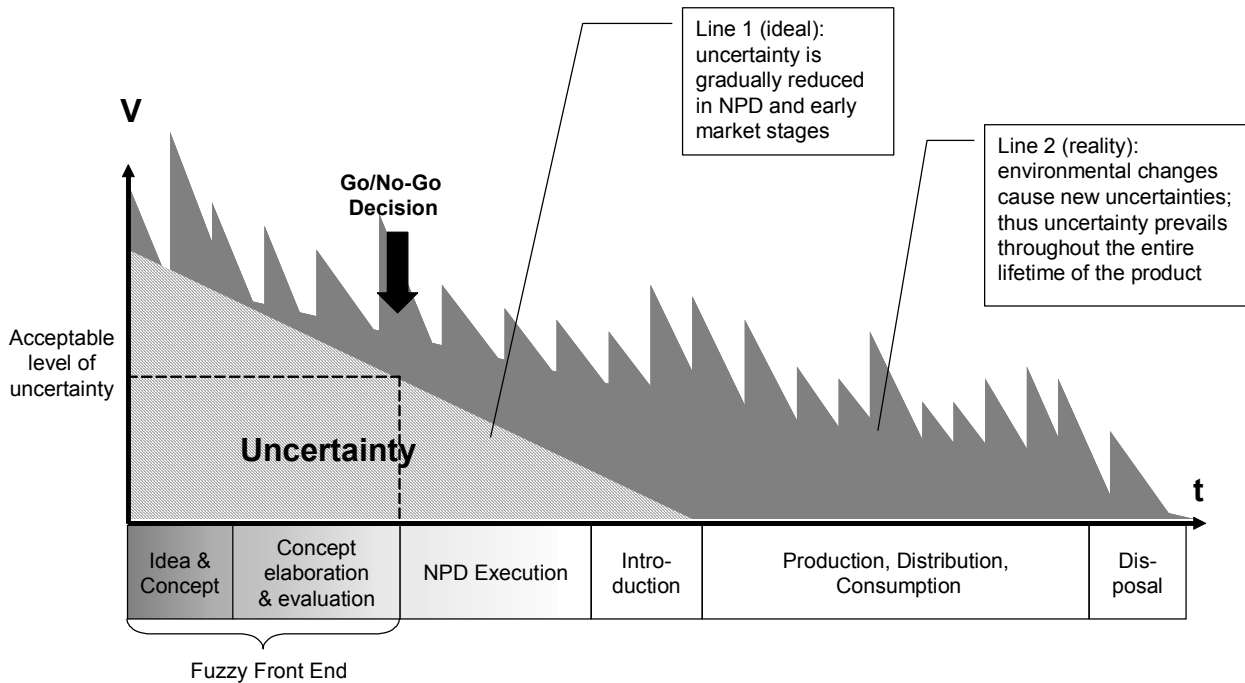

Figure 1: The challenge of uncertainty

Types of uncertainty

Four types of uncertainty can be distinguished: (1) Market uncertainty, (2) Technological uncertainty, (3) Environmental uncertainty, (4) Uncertainty about resource allocation.

(1) Market uncertainty - Product concept creation and definition implies "simulating what future customers will experience" [2, p. 22] when they buy, consume and dispose the new product. When companies produce durable goods, such as some consumer goods (e.g. washing machines), machinery (e.g. grinding machines, power plants), automobiles or aircrafts, they have to bridge considerable time spans between product development, when product features are decided upon, and product consumption, when these features are put to the test against customer requirements. In the automobile industry, e.g., typically a twenty year period elapses between the start of a car development project and the end of the disposal cycle, when the last use experience is made with cars that result from this project [2, p. 25]. Until then, use experience will influence re-buys and brand image, liability costs and revenues from after sales service. In some cases, there is a legal obligation to ensure recycling – e.g. in the European Union, where in 2006 car manufacturers will have to take back old cars and recycle at least 85% of the materials they contain without any charges.

The long time span elapsing between product definition and disposal poses problems for the FFE, because potential customer might not only have great difficulties to articulate there prospective demands but these demands may change. Throughout product development, future customer requirements will therefore always be to some extent uncertain and market uncertainty prevails [31, 58].

Market uncertainty, however, does not only result from uncertainty about customer requirements, but also from uncertainty about future competition: Competitors could launch new or improved products, either independent of the new product development project or in reaction to it, thereby threatening new product profitability. Furthermore, radically new products which open up new markets might attract new competitors (possibly with superior capabilities) applying strategies that utilize the innovator's experience.

(2) Technological uncertainty – Anticipating future market requirements is a necessary, but not a sufficient condition for product definition. In addition, product developers have to turn these requirements into product

features and production processes based on future technologies the performance of which may be uncertain or which may even not exist at the time of concept definition. When NPD managers utilize existing technologies only, they may not only miss opportunities offered by new superior technologies that will be available when the new product is produced and sold but also incur the risk of offering products which are not competitive if other companies integrate more advanced technologies. On the other hand, it is risky to base NPD on product and process technologies that are still under development or – even worse –have to be developed, because these technologies might not be available on time or might not be as effective as expected.

(3) Environmental uncertainty - Product concept creation and definition oftentimes are performed under high uncertainty about the general – economic, ecological, social and political - environment. Environmental uncertainty may either affect the product concept directly, (e.g., by restricting the new product's production because of new environmental protection legislation) or indirectly by influencing market and technical uncertainties (e.g. changes in customer requirements resulting from income decreases due to economic declines).

(4) Uncertainty about resource allocation - Finally, NPD managers are uncertain, how much resources should be allocated to a project and when to allocate it, because a confident "go" or "no-go" decision, based on a reasonably certain business analysis is often impossible in highly dynamic environments [31]. Although these uncertainties prevail through many stages of NPD they are extreme during the fuzzy front-end.

Causes of Uncertainty

Empirical research indicates that NPD projects are more prone to be successful, when uncertainty is reduced effectively in the early phases of product development through market and technical analysis [3]. However, many companies fail to do their "up-front homework" [4] because uncertainty reduction is all but a simple task.

In order to successfully deal with uncertainty, its underlying causes have to be understood. While some authors consider uncertainty simply to be a lack of information that can basically be cured through information gathering, Miliken [29] and Schrader et al. [43] take a different view by asserting that uncertainty is caused by an individual's perception of a situation. Milliken distinguishes three types of uncertainty [29, p. 136ff.]:

State uncertainty occurs, when decision-makers perceive their environment or a particular component of that environment (e.g. a competitor or a technology) to be unpredictable - usually because they do not know the environment's elements and their possible states and because they do not fully understand the interrelations between them. Effect uncertainty refers to an individual's inability to judge the impact of environmental changes (e.g. the loss in revenue due to a new competitor). This type of uncertainty occurs,

when causal relations among decision elements are not understood. Response uncertainty finally refers to a lack of information on possible response actions and/or their effects (e.g. the possibilities to use an evolving technology and its consequences). It can occur even though the decision-maker knows the decision-environment's elements and causal relations. All types of uncertainty are determined by the individual's view on the problem, i.e. his framing or "mental model" of the situation. Mental models govern, how uncertainty is perceived and dealt with.

When decision-makers consider a situation to be new and uncertain, they tend to question and modify their mental models of the decision environment, thereby giving leeway to innovative solutions. When they believe the situation to resemble a problem that they have experienced before, they apply their proven mental models, thus being able to transfer knowledge from past to present NPD projects. However, in complex situations, such as the FFE, problem-framing is problematic: similarities between problems are often ignored, while new problems are addressed through inadequate old mental models [43]. Empirical research has furthermore shown that many decision makers apply oversimplified models that lack important system elements and an understanding for multiple causal pathways. Also, multiple or long-term effects of a specific decision tend to be ignored.

Even elaborate mental models, however, do not prevent decision errors, because bounded rationality constrains the ability to use these models for the anticipation of system dynamics. Therefore, feedback loops tend to be ignored and future system states forecasts are oftentimes false. Frequently, present trends (e.g. growth rates) are extrapolated in the future, assuming monotony and linearity [10, 11, 50].

2) **Meeting the challenge of uncertainty - requirements**

Mental models that adequately model real-world situations and are used to their fullest potential are a prerequisite for dealing with uncertainty. Because of their limited information processing capacities, FFE decision-makers need methods and tools to support them in building and applying suitable mental models.

Front-end tools should therefore provide a holistic, system-oriented view on the FFE. This enables decision-makers to identify critical elements of the system in order to collect relevant information, and improves their ability to understand the dynamic relations between critical system elements, thus reducing state, effect and response uncertainty. Additionally, front-end tools should aim at enhancing information processing capabilities in order to make elaborate mental models manageable and reduce effect and response uncertainty. Finally, they should encourage "systemic learning" and the transfer of newly acquired knowledge among projects.

This kind of learning experience, however, is difficult to ensure: usually considerable time elapses between a front-end decision and its results. In the meantime other decisions have been made and exogenous decision parameters have changed

autonomously. It is therefore almost impossible to attribute an observable result (e.g. sales volumes) to a specific decision (e.g. the choice between two alternative product concepts). It is furthermore impossible to learn from decisions alternatives that have not been chosen - nobody will ever know, how the abandoned product concept would have performed.

In order to enable decision-makers to gain experience with the behavior of complex systems, some authors recommend the use of simulation techniques [10, p. 295ff; 47, p. 313ff; 50, p.33f], that are referred to as "technologies of the learning organization" [47. p. 313]. Simulation technologies make it possible to test different decision alternatives at relatively low costs and to evaluate potential impacts of present decisions on later phases. Thus they can contribute to FFE success. However, since no two NPD projects are alike, simulation models have to be easy to build.

3) The challenge of interdependency

The high uncertainty of front-end activities is aggravated by their reciprocal interdependencies. Upstream process stages have to make use of uncertain downstream information about constraints and opportunities arising in later stages of the product life cycle. Reciprocal interdependencies which have to be taken into account naturally exist between the development of a product and its use. Additional interdependencies exist between (1) present and future products, (2) different activities of product development, and (3) product development and production [58, p. 379f.].

(1) Interdependencies between present and future products may exist on a technical level, e.g. when NPD results in modules or product platforms that are used in existing or future products [44; 58, p.380]. Interdependencies may also exist on a market level: especially when deciding about the purchase of durable goods, customers consider future product options. They may decide to "leap frog", i.e. skip one product generation in favor of the next one [38]. Therefore the new product's features and its time of market entrance have to be carefully selected to make sure that the new product does not "cannibalize" existing products.

(2) Interdependencies within the NPD process may be horizontal, as well as vertical: While horizontal interdependencies result from parallel execution of related activities, e.g. the simultaneous development of product components that influence each other, vertical interdependencies occur when upstream process stages have to make use of uncertain downstream information about constraints and opportunities arising in later stages of the product life cycle. Process designs, e.g., have to be considered during product development, but cannot be finalized without a good understanding of what is to be produced.

(3) Interdependencies between product development and production become most obvious in the production cycle, when both product and process definitions are put to a test. Poor product designs (e.g. no consideration for manufacturability) and inferior process definitions (e.g. use of inadequate process technologies) lead to longer unit production times, additional production steps, and lower quality standards. In some cases, product definitions have to be reworked - usually with additional development and quality costs and time delays that can influence market entry schedules [58, p.380].

4) Meeting the challenge of interdependency - requirements

Interdependencies arise within the NPD process (e.g. between electrical and mechanical engineering) and between NPD functions and post-development activities (e.g. production and service). An important approach to dealing with these interdependencies is integration. NPD success rates improve, when different functional areas are integrated in the early phases of product development [34, p. 268; 40].

Integrating knowledge and experience from many different functional areas, however, is problematic, since experts have different educational backgrounds, different views on a problem and different professional languages to describe it. FFE decision-makers should be supported in overcoming these problems through suitable tools and methods.

These tools and methods have to make sure that developers reach a common understanding or mental model of their joint development task and its underlying assumptions. Therefore, transferred information should be embedded in its context, thus enabling team members to turn some of their tacit knowledge (judgment, intuition) into explicit knowledge. Furthermore means to store team knowledge are needed, because team members might change during project execution [39].

Applying a holistic "system view" at NPD and integrating knowledge from different experts are important means to address the problems of uncertainty and interdependency in the FFE. Both approaches can be found in theoretical works as well as in business practice. They are also embodied in the three front-end strategies that will be discussed in the next section.

C Front-End Strategies

Scientists and practitioners have reacted to the challenges of uncertainty and reciprocal interdependencies through three basic strategies depicted in Fig. 2: (1) reducing time-to-market, (2) increasing flexibility, and (3) front-loading of problem-solving. While reducing time to market and increasing flexibility primarily address the uncertainty problem, front-loading may be considered as an attempt to solve the interdependency problem.
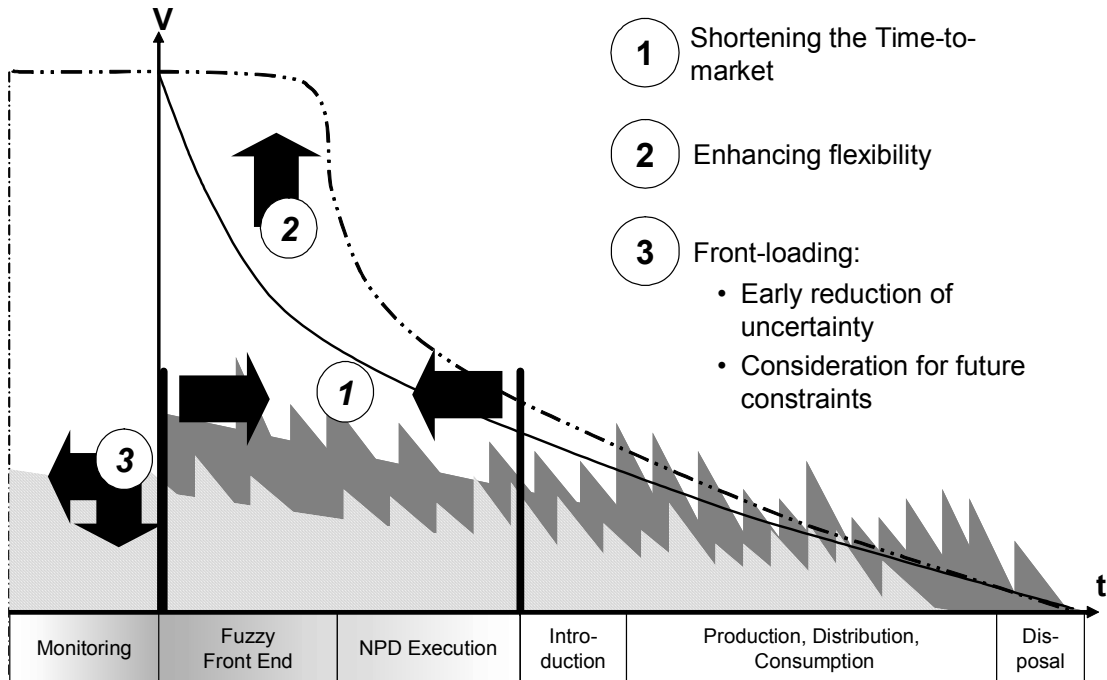
Figure 2: Strategies for the Fuzzy Front End

Shortening time-to-market reduces the risk that customer requirements and product technologies change between product concept definition and the new product's introduction and exploitation phase. In addition, it tends to increase the set of decision alternatives by enabling companies to pursue a pioneer strategy [37, p. 3ff; 49, p. 3ff; 59, p. 90ff.] and helps them to actively choose their optimal point of market entry. Time-to-market is greatly influenced by the length of the NPD process, that has been dramatically shortened in many industries [59, p.157ff] through the application simultaneous engineering (SE) principles: development activities are sped up, partially overlapped and executed in cross-functional teams, thus reducing interfaces, improving integration, speeding up information transfers and reducing the necessity of corrective changes [59, p. 198ff].

Enhanced flexibility is achieved through flexible design and production technologies (e.g. parametric construction, rapid tooling, and virtual laboratories) and through modular product architectures [53], as well as through parallel work on alternative product concepts and late design freezes [53; 58, p. 385]. Furthermore flexibility may be increased by keeping upfront investment low and allocating sufficient time and money to uncertain activities for probing and learning [31, 58, p. 385;].

Front-loading of problem-solving tackles the problem of interdependencies by anticipating future constraints and opportunities at the earliest possible point in time [52, p. 129 and 132; 58, p. 381]. In order to achieve this goal, Thomke suggests a system of "enlightened experimentation" [51] that mainly builds on the transfer of knowledge about problems and solutions between projects and on the intense utilization of rapid problem-solving techniques [52, p. 132]. Since no two NPD projects are alike, transferring knowledge from one project to another requires the ability to comprehend NPD as a system of interrelated elements and to identify critical system elements based on prior experience; Verganti characterizes this ability as "systemic knowledge" [58, p.387]. The critical system elements are attacked by modern design techniques such as rapid prototyping and CAD simulation which allow the technical and market-oriented evaluation of design alternatives prior to the product's material existence and at substantially lower costs than hardware prototypes [8, 51].

The decision on the intensity of front loading and the proper degree of flexibility are interdependent: if front-loading yields certain information, it is advisable to choose front-loading. If not, an early investment in flexibility can substantially reduce the costs of necessary corrections [58, p.385] by facilitating late corrective actions.

D Conclusion: Requirement for Front-End Management Support

Requirements for concepts and tools supporting the management of front-end activities result from the challenges of NPD front-end activities and the strategies recommended for their management, as well as from the behavior of managers and researchers confronted with these challenges. The most important requirements are summarized in Fig. 3.

Support of	Transfer and storage of information/knowledge based on	View at fuzzy front-end
• uncertain • imprecise • dynamically changing information Processing of information from • many information sources • different functional areas	• common understanding • transfer of information contexts and tacit knowledge • storage of team knowledge	• holistic, system-oriented • "systemic learning" Methods/technologies • simulation • models have to be easy to build and to apply • fast and easy updates

Figure 3: Requirements for concepts and tools supporting the management of front-end activities

III CONCEPTS AND TOOLS FOR FRONT-END MANAGEMENT SUPPORT

In the previous chapter, requirements for front-end support have been derived from the activities and challenges of the fuzzy front end. However, attempts to provide methodological or tool support have so far been rare - possibly because front-end processes seem unmanageable due to the prevalence of ill-structured, weakly formalized activities [32, p. 5]. The following section gives a very brief overview of the state of the art by shortly describing the few existing concepts and tools that address the requirements of front-end management[1].

A Traditional approaches

Traditional support tools from the marketing and engineering discipline, such as Quality Function Deployment (QFD) for product concept specification and elaboration [7, 41, 42, 46] as well as various approaches for product concept evaluation [48] and concept-testing [36] have serious limitations:

Many of them are ill-suited for radically new products, because they rely on relevant historic market data (e.g. market growth models), which is not available for really new products or is irrelevant in dynamic environments [36]. Other tools rely on consumer judgment (e.g. to estimate sales or to define product specifications), which is not reliable, unless respondents have sufficient prior knowledge about similar products [13, p. 10f.]. Consequently these tools are not suitable for radically new products that often bring about environmental change [55, p. 47] and force consumers to use new measuring scales in their judgment [5, p. 2].

Another limitation of front-end tools is that most of them fail to actively support the integration of different functional areas [41, p. 320 f; 42]. Therefore they cannot give

methodological support to the planning of front-end activities, for which cross-functional integration is critical.

Finally, existing tools do not support the entire front-end process, but mostly neglect concept development [41, 45].

B New concepts and tools

To overcome the limitations of traditional approaches to front-end support, a variety of new concepts and tools have recently been suggested. These new approaches ground on three concepts: (1) Scenario Analysis, (2) Knowledge Mapping and (3) System Thinking. The concepts and the tools available for their implementation will be briefly discussed in the following section.

1) Scenarios

Scenarios attempt to address the problem of uncertainty about future developments holistically: rather than trying to predict the future state of selected (critical) elements of the environment, they consider a number of possible future environments. Though they are well-established in strategic planning for more than two decades, they have only recently been applied to the FFE by Gausemeier et al. [14-16] and Urban et al. [55-57].

Gausemeier et al. [14-16] transfer the philosophy of multiple futures into product concept generation and link it with the idea of robustness. They suggest the use of product, technology and concept scenarios in order to obtain robust product concepts that yield the desired results, regardless of what future scenario comes true.

Product scenarios bear strong resemblance with the market-oriented scenarios in strategic management. They are employed to generate robust product strategies. Technology scenarios are likewise used for the identification of robust technology choices. They ground on the functional decomposition of the products – a step in product concept deployment that is well-known in engineering – and the subsequent assignment of alternative (future) technologies to the product functions defined. Concept scenarios are derived from scenarios on evolving, potential requirements of various

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[1] For a more detailed discussion refer to [45]

stakeholder groups (e.g. employees, customers, suppliers, public). They serve as mission statements for the development of future products and technologies, thus adding a visionary element to product and technology scenarios.

Due to the utilization of multiple scenarios the approach of Gausemeier et al meets the requirement of employing a holistic view. By providing robust product concepts it also meets the demand for planned flexibility. However, as is the case with all scenario-based approaches, its adequacy critically depends on the scenario builder's ability to develop realistic views of the future. Thus it cannot be assessed on the general level of the methodology but only on the specific level of the application.

Urban et al. take scenario planning one step further through Information acceleration (IA) [55, p. 326ff.; 56, 57]: to obtain reliable customer judgment on future products, the future is simulated. In that sense, the approach of can be characterized as scenario-based front-loading.

The authors use scenarios to describe and simulate the decision context that customers will encounter in the future, thus addressing the problem, that today's customers have difficulties to state tomorrow's needs and wants. Consumers are placed in a virtual environment that moves them forward in time and enables them to base their judgment on future situations. This is achieved through a multi-media computer system that allows respondents to browse through articles, to watch TV commercials and to interact with salespersons and users through video footage. Thus, respondents can employ the same information behavior they would employ in real-life decisions.

Due to the use of scenario analysis the suitability of IA also critically rests on the scenario-builder's ability to anticipate realistic futures. However, little guidance is given as how to integrate different experts' knowledge in the process of building scenarios. This problem is addressed by the concept of knowledge-mapping described in the next section.

2) Knowledge mapping

Knowledge mapping methods have been widely used to elicit and to communicate mental models of individuals or groups of decision-makers. Maps are graphical tools to represent – among others –conceptional, causal, and argumentative knowledge [18 p. 11ff].

Concept maps are a specific type of knowledge maps that visualize knowledge structures. They consist of concepts and propositions. Concepts are objects that individuals have experienced or have been told about. They are represented by nodes and linked by propositions or statements modeled by edges.

In order to support multi-personal and multi-functional NPD processes, Ramesh and Tiwana [39] use concept maps to model knowledge in collaborative product development. Their software prototype generates concept maps built from concepts that contain knowledge elements for the NPD process (e.g. a product's specific components, such as its power supply). Concepts can depend on or suggest other concepts (e.g. power supply depends on power demand) and

are usually based on assumptions (e.g. the assumption that the product will be sold in a target market with 220V voltage).

Concept maps are used to store team knowledge and to initiate communication. They may be linked to static documents (e.g. memos, work procedures, drafts, video clips) and to documents that are dynamically created, e.g. by searching the WWW. In addition, context information about new or changed knowledge components may be attached to all concepts answering questions such as who added the concept or proposition or when and why it was added. Whenever concepts or underlying assumptions change, a time stamp is created. Users are notified about the change and the concept map is updated. Thus, users learn about changes that occur in other functional areas but might affect their work. Furthermore, they can retrace previous steps in the NPD process in order to learn from prior mistakes or simply to understand, how a certain decision (e.g. a product specification) has evolved and what assumptions it was based on.

The visual nature of concept maps facilitates understanding of existing dependencies and contingencies between knowledge components, thus supporting adequate reaction to information changes and contributing to a shared understanding of the NPD process. The hierarchical nature of concept maps, however, makes it impossible to model the complex causal interdependencies of NPD. This can be achieved through another well-known type of knowledge map – the so-called cause maps or influence diagrams that are the key instrument for achieving system thinking.

3) System Thinking

System Thinking – the ability to see the world as a complex system of interrelated elements- has long been advocated by many authors [50, p. 4], who often suggest the use of cause maps to increase awareness of interdependencies and dynamics. Through system thinking, the desired holistic view on NPD can be achieved. Limited information processing capabilities, however, make it impossible for humans to test and apply causal models to their fullest potential without simulation techniques [50, P. 4]. System Dynamics provide mathematical models to assess system behavior, but require quantitative data. Furthermore, modeling is considered to be demanding and cumbersome in rapidly changing real-world situations [28].

Nadkarni/Shenoy [33, p.491f] and Cooper [5] have therefore suggested the use of Bayesian networks as a method that can quantitatively cope with the mostly qualitative information that prevails in the FFE. Nadkarni and Shenoy demonstrate the applicability of causal Bayesian networks for making inferences in the early NPD phases. Cooper uses Bayesian nets to improve the planning of radically new products.

Causal Bayesian networks [33] are directed acyclical graphs – similar to cause maps - with nodes that represent concepts and arcs that describe (conditional) causal relations among these variables. They are used to represent knowledge domains with uncertain knowledge. Uncertainty is modeled

through the distinction between different concept states and the assignment of probabilities to these states. Depending on its position in the network, the probabilities assigned to a concept node are unconditional or depend on the probabilities assigned to other nodes. Probability distributions can be calculated for all concepts [33, p.480]. If e.g. the probability of a long or short market cycle is conditional on low or high market dynamics, a change in probabilities for market dynamics will also affect the probability distribution of the market cycle.

Once the causal Bayesian net is constructed, new information (e.g. the occurrence of one out of several possible concept states or exogenous changes in the probability distributions) is processed by calculating posterior marginal probabilities for the concept states and comparing posterior with prior marginals. Thus, the impact of changes can be assessed. Furthermore, the most probable future scenario can be identified. In that sense, Bayesian nets are dynamic planning documents that allow continuous updates of all system elements [5, p.11].

However, the modeling approach puts high demands on knowledge engineering: feedback loops and indirect causality have to be eliminated, mistakes tend to add up and the number of conditional probabilities easily exceeds a manageable level, if the number of concepts is not handled restrictively [5, p.8ff.]. Consequently, Bayesian nets at present cannot fully handle the complexity and interdependencies of the fuzzy front-end.

The new concepts and tools described in this section do not offer ready-made front-end solutions but present "ways of thinking" that can and should be incorporated in future front-end support tools. In the following section, a conceptual tool for decision support in the early NPD phases is introduced,

that draws on the existing concepts and attempts to transcend them by adding further capabilities in order to meet the requirements of the FFE.

IV   FCM-BASED ACTION SUPPORT FOR THE FUZZY FRONT END - A CONCEPTUAL SYSTEM

The management support system described in this chapter is based on psychological research about the process of action regulation in complex systems. Methodologically, it uses Fuzzy Cognitive Maps (FCM) as a modeling approach, thus circumventing most of the drawbacks of Bayesian nets without giving up their merits. Both concepts will be briefly introduced in the following section, before the backbone of the system's architecture - FCM modeling - is described in detail.

A   Conceptual basis of the action support system

1)   Theoretical basis: action regulation

Planning and decision-making in complex situations - also referred to as the process of action regulation - is a multi-step process that decision-makers are usually not fully aware of. Many decision errors occur, because activities are faulty or important steps are skipped. To investigate the typical decision errors discussed above, Dörner et al. [10-12] have developed an idealized process model which comprises the six activities or "building blocks" depicted on the left hand side of figure 4: (1) situation analysis and goal formation, (2) modeling, (3) prediction, (4) planning, decision, action, (5) monitoring of effects and revisions, and (6) collection and processing of background information.
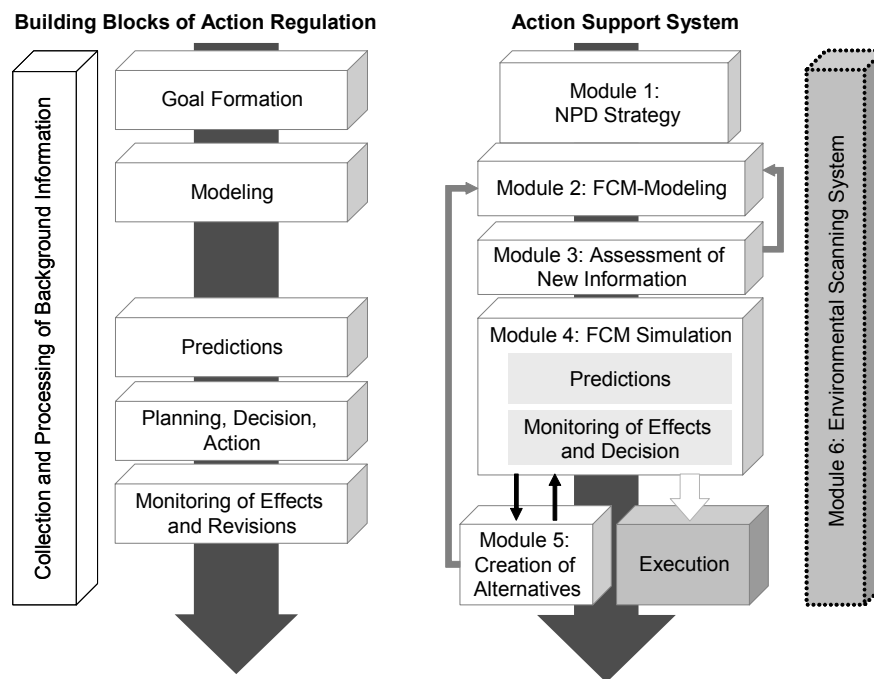

Figure 4: Action regulation and corresponding modules of the actions support system

Decision errors occur throughout the entire action regulation process and can usually be attributed to distinct process steps. Therefore, systematic support of all six activities is highly desirable. To provide this support, the proposed support system's structure which is depicted on the right hand side of figure 4 contains six modules corresponding with the action regulation activities.

While modules 3 through 6 are permanent activities throughout the entire fuzzy front-end modules 1 and 2 usually have to be passed only once, when the development project starts. In module 1, the goals of the NPD project are formed; conflicting goals are identified and prioritized. Furthermore, the general NPD situation (customer needs, competitive situation, technological choices, planning horizon, level of uncertainty, extend of planned flexibility, number of alternative scenarios to be considered, influential stakeholders, etc.) is specified and evaluated against the project goals. In Module 2, the NPD situation is modeled through so-called Fuzzy Cognitive Maps (FCMs), which will be introduced in detail in the following section. This sets the stage for modules 3-5.

Module 3 serves to evaluate the impact of new and changed information, which becomes available during the development process. When no impact is expected, the information can be ignored. When the new information forces decision-makers to adapt their causal models, Module 2 is revisited and existing FCM models are changed. Finally, when information impacts are likely, but existing models remain unchanged, Module 4 is activated. Using FCM inference it simulates the consequences of new information and/or alternative NPD decisions on project success. When simulations show, that the present plan is no longer adequate in view of the new information, Module 5 is used to generate alternative problem solutions, which are decided upon with the help of Module 4. Module 6 scans and monitors the business environment for weak signals to make sure that strategically relevant information becomes available as early as possible. Strictly speaking, this module is not a part of the action support system, but a company-wide strategic management function.

2) Methodological basis: fuzzy cognitive maps (FCMs)

Fuzzy Cognitive Maps (FCMs) [24, 25] are used to analyze interrelations between phenomena that are graphically represented in causal maps or influence diagrams. Concepts (= nodes) are linked through arrows that represent causality. The arrows are denoted with "+" or "-", depending on what type of causality exists. Positive (negative) causality between two concepts A and B implies that an increase in A causes an increase (a decrease) in B. Like all directed graphs, FCMs can be translated into square connection matrices.

FCMs are based on (simple) causal maps, but overcome the causal maps' severe limitations: traditional causal maps deliver indeterminate results, when a concept is influenced through an even number of positive and negative in-going arrows. Furthermore they cannot model non-monotonic

causal relations [1, p. 70ff.]. FCMs address these problems by attributing (fuzzy) weights to the arrows and by applying neural network theory to the underlying causal map [24]. Fuzzy edge weights like "a little" can be easily obtained from experts and can be translated into crisp values in the interval [-1; 1], thus allowing for different degrees of causality. Concepts may take on values in the interval [0; 1] and are consequently not limited to binary states (1 = "on"; 0 = "off"), but can take states in-between. Therefore FCMs are "fuzzy", even though no fuzzy sets are calculated.

To calculate the network, FCMs are regarded as a simple form of recursive neural networks [24]. Each concept corresponds to a neuron. Concepts are non-linear functions that transform the path-weighted activations directed towards them (their "causes") into a value in [0, 1]. The functions are usually bounded monotones, such as the sigmoid function. Also, simple threshold functions are used [25, p.888]. When a neuron "fires", i.e., when a concept changes its state, this will affect all concepts that are causally dependent upon it. Depending on the direction and size of this effect and on the threshold levels of the dependent concepts, the affected concepts subsequently may change their state as well, thus activating further concepts within the network. Since FCMs allow feedback loops, it is well possible that the newly activated concepts influence concepts that have already been activated before. Thus, the activation spreads in a non-linear fashion through the FCM net. It usually stops after a few cycles in a fix point or limit cycle, but chaotic behavior is possible as well [9, p. 10ff.].

Mathematically, spreading activation takes place by multiplying a state vector of causal activation with the square connection matrix derived from the FCM graph and by thresholding the result in accordance with the concepts' functions. The resulting new state vector is again multiplied with the connection matrix. The process is repeated until stability is reached or a stop criterion is met. Thus a holistic view at the entire network is realized.

Using FCMs, the internal dynamics of causal maps can be investigated. Also, "what-if" questions can be answered by changing input state vectors and exploring the resulting future states of all concepts. This makes "hand-on" experience with the internal dynamics of the modeled system possible.

FCM-modeling is relatively easy, because comprehensive graphical representations (causal maps) and natural language descriptions (causal weights) can be translated into mathematical models without sophisticated knowledge engineering tasks. Furthermore, feedback loops and indirect cause-and-effect relations can be modeled, thus allowing experts to model the world "as they see it". Modeling may be based on interviews, text analysis or group discussions.

FCMs are easily modified or extended by adding new concepts and/or relations or changing the (fuzzy) weights assigned to relations. Unlike additions to Bayesian nets, additions to FCMs do not require the reassessment of already existing concepts, such as the calculation of new conditional

probabilities. Experts can therefore use one expert's FCM as a starting point and extend it successively at different times and places. This way the integration of the knowledge of various experts is possible.

Individual experts' cognitive maps can be easily combined [25] by asking individuals not for the strength, but only for the existence and the direction of causality between concepts, thus establishing simple connection matrices. The different matrices are summed and divided by the number of experts to normalize the edge in [-1; 1]. To account for different levels of expertise credibility weights can be used.

B System Architecture

1) FCM models - the backbone of the system

The action support system's backbone are four linked FCM models that depict the NPD situation (see figure 5). These models are constructed and applied in modules 2 through 4.

The environment-requirement model describes environmental trends and their impact on customer requirements. The technology-component-feasibility model links technological trends with design characteristics embodied in potential product components. These two models ensure that knowledge about environmental dynamics is systematically translated into product requirements and technical problem solutions. They contain elements that are not project-specific and may be utilized to link environmental scanning and monitoring with ongoing NPD projects.
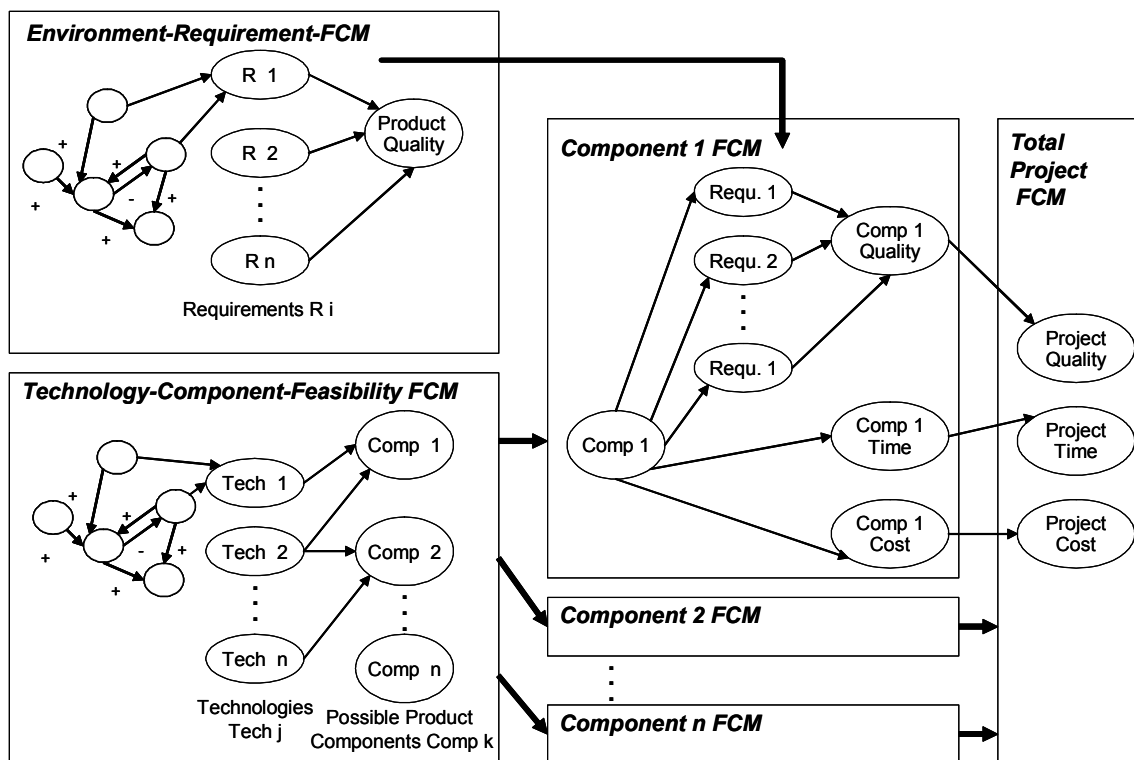

Figure 5: Four FCM Models and their Linkages

The component models use FCM to match customer requirements and design characteristics for all major components of the product. They may be considered as early predecessors of the "House of Quality" oftentimes employed within QFD in later stages of the NPD process. They exceed the scope of the "House of Quality", however, by revealing the causal effects of different components on time and costs. The component models should be substituted by QFD methods as soon as product features and requirements are sufficiently certain and precise.

The component models for all components of a product are integrated into the total-project model that allows qualitative statements about project quality, i.e., meeting of requirements, project time and project costs, and that is the starting point for a more thorough, quantitative analysis. The total-project model should be discharged when reliable quantitative data become available through project management.

2) Application of FCM models - an example

In order to illustrate the approach, a fictitious NPD project from a manufacturer of wind turbines will be used. Traditionally, wind turbines in Germany have been used by ecologically conscious private persons, farmers and small companies to produce electricity for their own use. A rapid increase of technical performance and high energy prices,

that result from a federal law allowing surplus wind electricity to be fed in the public electricity network at guaranteed prices have recently shifted wind turbine use: most turbines today produce electricity for sale, rather than to cover the producers' own needs. With turbines growing in number and size, however, resistance against wind energy develops, even in "green circles". Furthermore, private electricity companies protest against the high prices they have to pay for surplus wind electricity. These environmental trends and their impact on customer requirements can be modeled in an environment-requirement model, excerpts of which are displayed in Fig. 6.

Environmental forces

Customer Requirements
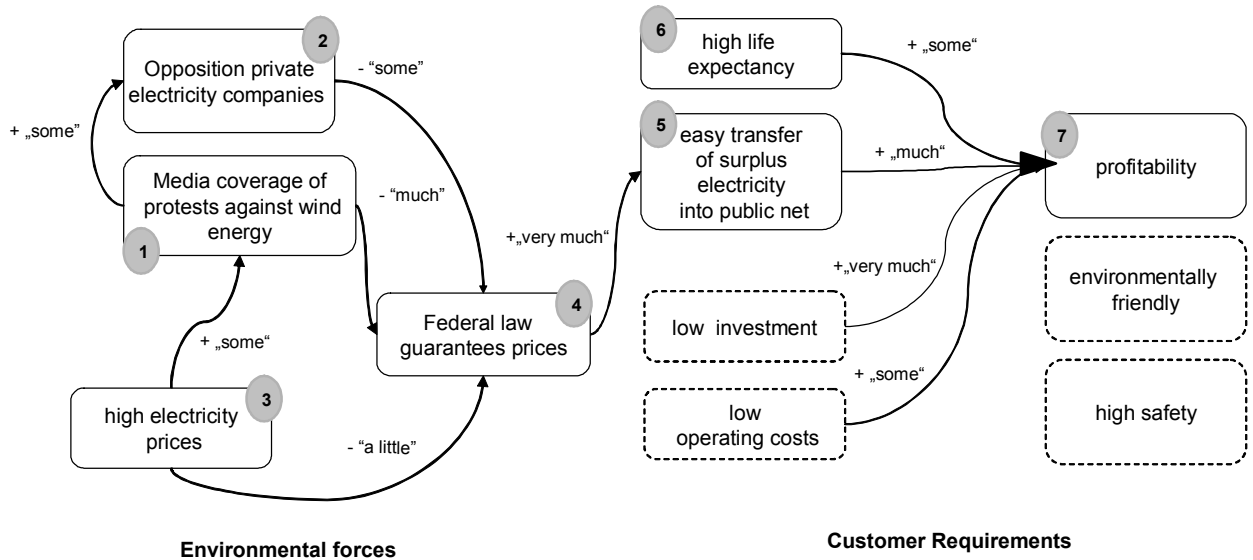
Results	C1	C2	C3	C4	C5	C6	C7
Start	0,000	0,000	1,000	0,000	0,000	0,000	0,000
t=1	0,622	0,570	1,000	0,278	0,575	0,500	0,664
t=2	0,622	0,577	1,000	0,269	0,569	0,500	0,664
t=3	0,622	0,577	1,000	0,268	0,567	0,500	0,663
t=4	0,622	0,577	1,000	0,268	0,567	0,500	0,663

Results without exogenous change of C3 (internal dynamics only)

internal dynamics	0,562	0,570	0,500	0,303	0,575	0,500	0,664

Figure 6: Excerpts from an environment-requirement FCM for the development of a wind turbine

When new information becomes available - e.g. an increase of electricity prices because of higher oil prices - this information may be evaluated with the aid of the FCM developed. If the concept is important, but not yet a part of the FCM, the FCM-model has to be augmented. If the information results in changes of the strength or direction of causal links edge weights have to be adapted. If the concept is neither important nor part of the FCM, it can be ignored.

In our case, electricity prices are already included in the model (concept 3). To assess its effects on the network, concept 3 is "turned on". The FCM settles down after three cycles and delivers the state values for all concepts of the FCM shown in figure 6. These values can be used to judge the impact of the information change by comparing them with the previous equilibrium state values. They may also be compared against target values that have been set prior to the simulation.

Profitability, environmental friendliness and safety influence (among others) the concept of total product quality, which serves as an important target value (see Fig. 6). In the example case, profitability (C7) remains almost unaffected by the information change (C3): the value computed for C7 changes only marginally from 0,664 to 0,663 when high electricity prices occur. Consequently, product quality (ceteris paribus) will also be unaffected by high(er) energy prices. If, however, product quality had changed beyond a certain tolerance band, this would force product developers to investigate the customer requirements that have brought about the change and eventually to modify the product concept accordingly. This subsequently could lead to changes in the total project FCM. Thus, the impact of relevant changes in the business environment on different product components as well as on total project costs, time and quality can be assessed. Since no substantial effects on product

quality show up in our example case, there is no need for the wind turbine manufacturer to reconsider his NPD planning assumptions.

NPD planning assumptions include assumptions about technologies: some components are only feasible, when new technologies are available on time, at reasonable costs and with the required performance. Changes in the technological environment can therefore affect the choice of product components. These causalities are depicted in the technology-component-feasibility FCM. In case new information would cause component feasibility to fall below a certain target level, component FCMs would have to be reviewed accordingly. This can lead to new product architectures with new components and new component-specific FCMs. It can furthermore result in component quality, time and cost variations. Finally, impacts on the project level may result, too.

C Discussion and conclusion

In Fig. 3 a set of requirements for front-end management support systems was established, which serves as a yardstick for the discussion of the proposed action support system. As pointed out, support tools should be able to deal with imprecise, uncertain and changing information. FCMs allow experts to build quantitative models based on their fuzzy views on concepts and causality among concepts, thus meeting this requirement.

Like scenario-based approaches, FCMs deal with information dynamics and uncertainty by allowing a look at alternative futures. Decision-makers can use simulation techniques to identify critical system elements and to assess the dynamic effects of information changes on possible future outcomes. They are thus able to gain "hands-on" experience with the modeled system's dynamics. FCMs thus provide a holistic view at the front-end and contribute to "systemic learning".

Knowledge acquisition with FCMs is rather simple, because experts can use natural language to describe concepts and causal links and organize their knowledge graphically. Furthermore, FCMs from different experts can be easily combined. Thus, the requirement to process information from many sources and different functional areas is met.

The individual experts' FCMs elicit their view on the problem and make it accessible for other team members. This is an important prerequisite for reaching a common understanding on the decision problem. The integrated FCM of all experts may serve as a means to store team knowledge.

Since FCMs are easy to build and to update and do not require elaborate additional training of the users, simulation models can be applied to NPD problems despite the fact, that no two development projects are alike and team members vary. Also, changes in the environment and in its perception can be easily implemented.

From evaluating the proposed action support system against the requirements of the fuzzy front-end it may be inferred, that it holds the potential to substantially improve front-end management. It is, however, still in a conceptual stage and has not yet been tested in real-life NPD projects.

Consequently, several open questions wait for future research:

Since the utility of FCM models strongly depends on the quality of the underlying causal maps, identification of experts and elicitation of their cognitive maps is a crucial activity. The identification of experts could be addressed through adapting a methodology by Lüthje [27] that was developed to identify progressive customers to be integrated in NPD as lead users. The elicitation of experts' cognitive maps requires the development of new approaches, because existing methods – mainly interview techniques - are time-consuming and not designed to capture weights of causal links.

This problem is closely linked with the problems involved in clarifying concept meanings in order to combine different individual FCMs. The use of ontologies should be investigated in this context.

When applying large FCM models, it is possible that unexpected system behavior occurs. More research is needed, to find out if and under what circumstances the two extremes - chaotic behavior or (almost) total stability regardless of the inputs - do occur in FCMs that describe "real-world" problems, and whether such behavior is in accord with the "real world". Also, means to navigate in large, integrated FCMs are required.

Considering the potential benefits from the FCM-based action support system presented in this paper the research efforts necessary to find answers to these questions may represent attractive investment opportunities for researchers.

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