Proceedings of ICAD2002
Second International Conference on Axiomatic Design
Cambridge, MA – June 10-11, 2002
ICAD 018

THE INNOVATION PROCESS AND THE PRINCIPAL IMPORTANCE OF AXIOMATIC DESIGN

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1 ABSTRACT

The industrial production system is a living system that has to be managed by *mean*. It is our main engine of wealth where productive use of machines amplifies our effectiveness in meeting defined needs. The innovation process is the dynamic part of this system. This is the process where new products and production processes are created.

Effectiveness in industrial processes requires quality and productivity. Quality is understood as meeting customers´ requirements, surprise and delight. Quality requires innovation in order to be dynamically adapted to changes in customers´ expectations. Productivity is expressing ability to meet quality with optimal use of resources. To strengthen industrial effectiveness we need a strong scientific base for innovation processes.

Axiomatic criteria in the decisions belonging to innovation processes have a powerful potential to increase quality and productivity in industrial production. This paper aims at explaining why and how, furthermore addresses it a strict handling of competence.

Key words: production, innovation, axiom, competence

2 INTRODUCTION

The competition on the global market of today entail increased demands on companies' ability to produce and develop products. In order to be competitive the focus of today should, more then ever, be on productivity and quality in both the innovation- and the production processes. However, many companies are still working with a *build, test and fix* (BTF) approach in these processes, instead of working with a *requirement, concept and improve* (RCI) cycle. That is, they are not focusing on getting it right from the start, which results in deficient quality and low productivity in both the innovation- and the production process. This will also, in the long run, result in an inefficient engine of wealth.

Achieving a RCI cycle requires a tight co-operation and knowledge exchange between different occupational groups, traditionally belonging to different departments. Moreover, an understanding of the fundamental principles for the innovation- and the production process is required. This understanding provides a transparency [Kjellberg, A. Moestam, A. 2001], in the processes. This transparency, in combination with the right competence, enables good decision-making resulting in fulfillment of the goals for the processes.

One of the most important sub-processes in the innovation- and production process is the development process. The development process is the sub-process that most clearly is connected to decision-making. This is the reason for us to more thoroughly examine this sub-process.

Perhaps the most fundamental view on the development process is to consider it as a way to transform something from state A to state B, where state A represents the starting point and state B the target point, that is, the goal.

When moving from A to B the decision-making, naturally, plays a significant role in terms of achieving both high quality and high productivity. A good decision in a development process is a decision that, when carried out, gives an effect that brings you the closest way to the goals that were set up for the development process [Fagerström and Moestam Ahlström, 2001]. However, the first challenge is, naturally, to find a state B worth striving for.

With this background the importance of a sufficient supporting system for good decision-making becomes obvious. This led us to the following research question:

> Is it possible to define an axiomatic theory for the decision-making in the innovation process?

This paper will not provide an exact and detailed answer to all aspects of this broad question. It will rather contribute with fundamental aspects, which helps engineers to better understand the role of good decision-making in the innovation process.

2.1 INNOVATION, PRODUCTION

All human activities must be properly planned first and then executed. In industrial processes planning is innovation and execution is production and distribution, see **Figure 1**. Innovation is primarily an information and knowledge development process employing our cognitive and visionary creative abilities. This requires specific competence and can be enhanced from problem solving support. Production is action very much dependent on our human emotions and has to be stimulated by leadership and company culture to develop competence, confidence, interest, belonging and joy. Action without knowledge is waste and can even be dangerous. Knowledge without action is also waste.

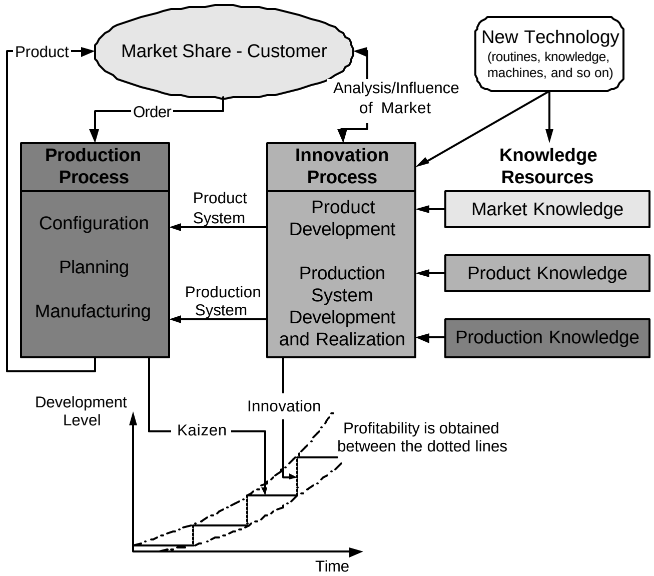

Figure 1 The industrial process contains innovation processes and production processes. In the innovation process products and production systems are created. The production system is initiated from customer orders and cultivates material to carry functions appreciated by the customers.

Sustainable industrial production must satisfy customers, shareholders and employees without harming nature or be hazardous to humans. Innovation, quality and productivity are elements in a strategy for industrial production as our engine to drive *wealth, prosperity and peace*.

Understanding *mean* [Johnson and Bröms, 2000] has to start with accurate definition of requirements and needs. Innovation processes have to be guided through accurate and competent decisions based upon firm criteria focussing quality and productivity. Competent decisions also demand strict and strategic definition of competence requirements.

Good decisions require defined goals. In industrial innovation processes goals must be defined based upon knowledge about customers´ needs as well as expectations from shareholders and employees. If we base our decisions on an axiomatic theory it would be possible to increase creativity as well as our ability to meet defined requirements.

2.2 AXIOM

When searching for axioms it is most important to understand and define what an axiom is. The Swedish National Encyclopaedia has the following definition:

> "*Axiom* (Greek axioma appraisal, assessment, opinion, statement, which without proof is considered to be true), in everyday speech it means an obviously true statement. In science an axiom is considered a principle that in itself is not the subject of proof but which is serving as the base for the proof of other statements (Comp. "Postulate"). A scientific discipline is said to be *axiomatic* or to be developed using a *axiomatic methodology* if all concepts in use are explicitly defined with the aid of a number of in beforehand defined basic conceptions, so called *primitive conceptions*, and all statements (theorems) within the discipline are derived as logical consequences from a number of in beforehand stated *axioms*. The basic statements and the axioms are together delimitating an *axiomatic system* or an *axiomatic theory*." [Nationalencyklopedin]

2.3 TOOLS, METHODS AND FUNDAMENTAL PRINCIPLES

In engineering design all aids ranging from theories and axioms to software systems, generally are considered tools. This is natural but not desirable as it confuses our understanding. It is necessary to distinguish between tools, methods and basic principles.

In the hardware domain we don't create this confusion so easily. Let us take a simple example:

If you are going to drive a nail into a piece of wood using a hammer, you know that the hammer is the tool. You also know that the method is to grab the handle of the hammer and swing the head so that it hits the head of the nail. To be able to succeed you have to know the method and you have to train not to hit your thumb and not to bend the nail. In other words, you have to obtain competence. Those of us who know the theory of mechanics also know the theory behind this process: The dynamic energy of the head of the hammer $(m*v^2)/2$, where m is the mass of the hammer and v is the end velocity before hitting the nail is transferred to the nail so that it moves into the wood material against friction and deformation resistance. The dynamic energy is transferred into nail motion according to the following equation: $(m*v^2)/2=(1-e)*s*(u+d)$, where e is the loss factor, s is the distance the nail moves at one hit, u is the friction force and d the deformation resistance force.

It is equally true that we naturally distinguish between tool, method and theory when we are dealing with machining, for instance turning. We know that the lathe is the tool; the method is turning and the cutting theory being the scientific theory behind this operation. To gain knowledge is critical. Competence for a specific task is based upon knowledge and experience (training).

It is important to be equally specific when dealing with tools, methods and theories in engineering design. We must base methods and tools on fundamental principles validated in accurate research. It is the competent use of such principles in innovation processes that can guarantee products meeting the requirements and expectations of the customers. If we could define and use an axiomatic theory of design we would open up for creativity and increase quality and productivity as well as competence.

Tools and methods are all the time exposed to development into higher efficiency, whereas the fundamental principles are the same, or being gradually more accurate by adding new findings from research. This dynamic development of tools leads to ever changing demands on competence. Competence can be more robust if it is based upon fundamental principles.

We think that the collection of all methods and tools in engineering that exist and are further developed today can be regarded as a *forest of possibilities*. The *fruits* that can be found in this forest are the fundamental principles and axioms. These principles are expressing fundamental truth that we can base our decisions on when developing products, manufacturing processes as well as total business processes.

2.4 CONTRIBUTIONS FROM AXIOMATIC DESIGN TO A SCIENCE BASED DECISION THEORY FOR DEVELOPMENT WORK

Axiomatic Design as proposed by [Suh, 2001] is in this sense especially important as it is based upon a few very well known and important principles to follow in order to obtain quality when developing something, such as products and processes.

Let us try to express the fundamental principles that the method Axiomatic Design according to Suh is based upon:

1. The design is a mapping between four domains, Customer-, Function-, Design- and Process-domain. The Product or Process that is being designed belongs to the Design domain.
2. The product is possible to describe as a hierarchy of Design Parameters. For each design parameter DP the functional requirement FR answering the question *why this DP?* is to be found at the same position in a function tree in the function-domain. For each DP also the process variable PV, that is chosen to create that DP, answering the question *how to get this DP?* is to be found at the same position in the process-tree in the process-domain.
3. The FRs are related to the customer domain as answers to the question *how could the product satisfy the customer?* The FRs on the highest level have to consist of the minimum set of necessary FRs to meet the overall intention with the product or process, to satisfy the customer. On all levels FRs must be defined based upon a need for independence. Each FR has to be specified quantitatively with target value and tolerance in order to be specific enough for decisions about alternative DPs.
4. On each level in the product tree there is a one -to-one correspondence between FR, DP and PV. The tree-structure is the same in the function-, design- and process-domains. The question *how?* leads from FR to DP to PV and the question *why?* leads from PV to DP to FR. FRs define the target satisfying customers. DPs have to be chosen to satisfy FRs. In the same way PVs have to be chosen to produce DPs. This is a basic principle necessary to follow in concurrent engineering. The PVs will then become bi-directional links between the product and the process design [Fagerström, et al., 2002].
5. Depending on the choice of DPs, the FRs can become coupled, decoupled or uncoupled in their functional behavior. An uncoupled design is the easiest to operate. However, setting the DPs in correct sequence can operate a decoupled design. A coupled design finally requires iteration when setting the design-parameters, which complicates the innovation process as well as the use of the product. The degree of coupling can be analyzed in the design-matrix, which expresses the connection between the vector of DPs and the vector of FRs. Axiom 1, expressed as a design rule: *maintain independence between functional requirements* is referring to this fundamental connection between FRs and DPs. The same relation exists between DPs and PVs. Axiom 1 is obviously the most fundamental principle to base decisions leading to quality upon.
6. A design specified in terms of DPs has a certain probability to meet all the specified FRs within given tolerances. Each DP has a certain functional statistical distribution which in relation to given target and tolerance defines the probability for that DP to meet the actual FR. A design with high probability to meet FRs within tolerances has also a high probability to satisfy customers and is therefore preferable. Axiom 2 m*inimize information content* is referring to this fundamental connection. Information content (I) is here defined as:
$$I = -\sum_{i} p_i \log p_i$$
where p is the probability to meet the requirements. In an uncoupled design smallest sum of information content is equivalent to highest probability to meet all functional requirements within tolerances. Axiom 2 is the second most natural principle to base decisions leading to quality upon.
7. Each level in the FR-tree is constrained by the next higher level in the DP-tree. In the same way each level in the DP-tree is constrained from the next higher level in the PV-tree. None of the trees therefore can be created independently. Zigzagging over the three domains is necessary in the detailing of the design and the processes to create it.
8. In order to meet the FRs, the DPs have to be selected based upon Axiom 1 and Axiom 2 and the PVs have to be selected to meet the requirements defined by the features of the DPs according to the same axioms.

These fundamental principles are important and possible to use if we have complete information about the DPs and the PVs including their functional behavior together with accurate information about influences from the environment, where products and processes are intended to work. This is a good start and it is worthwhile to be ambitious to develop enough knowledge to obtain this information. With this information it will be possible to make accurate and quick decisions. Requirements based upon emotions such as esthetic qualities are often of dominating importance to customers and have to be carefully handled with additional approaches. In this paper we are focusing technical functionalities only. These are possible to handle in an objective way.

3 DECISIONS RELATED TO PRODUCTIVITY AS A PROPOSED ADDITION TO AXIOMATIC DESIGN

In principle we have always to decide on quality first and axiomatic design as to Suh [Suh, 2001] together with robust design as to Taguchi [Phadke, 1989] is sufficient for this.

Moreover, we have to consider productivity as well in taking decisions about both DPs and PVs. Productivity is considering the energy and time we have to spend in order to reach the goal defined by the FRs.

In order to understand this conceptually, let us take a helicopter view on the innovation process and ask ourselves: *What are we in essence doing when we create products?*

Obviously, we are extracting materials from nature and process them into products. We are not paying for the natural resources as such. We are exploring them as free resources. We process the material with energy into products. In order to succeed we have to control the energy accurately with information. To acquire and develop this information into that information which we need in order to define the products and to control the processing energy, we have to do work, which also requires energy. It is true that the products also contain information and that we are using material also in the processing of the material. This, however, doesn't in principle change our overall observation. In conclusion: We extract materials from nature and process it with energy that we control with information that also requires energy to access and cultivate.

Now, what do we have to pay for, in order to realize products?

Energy! Yes, obviously our cost is a measure of the total energy we have to use in order to be able to design and produce the products. Naturally, cost as measure of energy is a very inaccurate one, as it is distorted from market prizing, taxes and interest rates. Interest can be seen as a payment for energy offered to create buildings and tools that we use as well as products in processing. From a practical point of view, however, it is correct and relevant to use cost as a measure of the energy that has to be offered, in order to design and to produce the products at hand. Increased competence is an important way to reduce this energy/cost.

After quality therefore energy requirement, which might be measured as cost, is the next decision criterion that has to be used in engineering development. We could formally express this as a decision rule based on an Axiom 3: *minimize energy in the selection of design parameters that are meeting the functional requirements*. This third axiom is a productivity axiom expressed as cost to meet a defined target, in this case defined in terms of FRs as above.

Productivity is both a matter of selecting or designing the process and a matter of waste. Waste occurs both as energy waste and material waste. The cost for waste of material is, as explained above, cost for energy as well. Efficiency should be expressed in percentage and defines the fraction of the input that is the useful output. Productivity is a measure of efficiency. However, the dimension is number of produced units per unit of currency.

Is this enough? How about time? We are often concentrating our attention to time, as lead-time, such as time to market (TTM) and time to customer (TTC). The answer obviously is that time is very essential. Intensity seen as the power that is used (energy per unit of time) is playing a major role. This means that we need an Axiom 4 as a decision criterion for time: *Minimize time in the selection of DPs and PVs meeting the FRs according to Axiom 1 and 2* In principle those four decision criterions expressed as Axiom 1 - 4 can guide decisions in any development work. The order between decisions according to effort (cost) and time is arbitrary. Especially in meeting short market - windows short time is more important than low cost. IT - industries are facing this condition today.

Expressed as axioms (observable truth) these four principles can be expressed in the following way:

Axiom 1: A design maintaining the independence of functions is superior to coupled designs.

Axiom 2: A design with higher probability to meet the functional requirements within specified tolerances is superior.

Axiom 3: A design requiring less energy to realize is superior.

Axiom 4: A design requiring less time to realize is superior.

The decisions related to quality dealing with functionality and certainty has to be taken first. The decisions related to productivity have to be taken afterwards. Axiom 1 must precede Axiom 2. Axiom 3 and 4 have to be used afterwards in arbitrary order. If we have difficulties to meet an axiom of higher order we have to go back to previous level and reconsider the design decisions.

Cost and time can also be defined as constraints (maximum allowed cost or time). In this case they are active in the selection of the acceptable alternative solutions according to Axiom 1 and 2 and are not needed as axioms for separate decisions. However, it is our opinion that cost (energy) and time always have to be minimized. If we apply them as constraints there is a risk that we are not obtaining the best productivity. We are satisfied if we just meet the constraints. Therefore it would be better to use these additional axioms as decision principles, **Figure 2.**

DECISION AND CRITERION IN DEVELOPMENT WORK

DECISION	CRITERION	PRINCIPLE	EFFECT
Functionality	Functional Independence	Axiom 1	Quality
Certainty	Max. Probability	Axiom 2	
Robustness	Min. Variance Sensitivity	Rob. Design	
Effort	Minimal Energy	Axiom 3	Productivity
Access	Minimal Time	Axiom 4	

Figure 2 Decision Theory for Engineering Design.

In case we don't have enough accurate information we have to tune the DPs and PVs to minimize distribution. This is known as Robust Design and comes principally after the decisions according to Axiom 1 and 2 [Phadke, 1989]. We are not going deeper into this problem here.

It is also necessary to be ambitious in defining the FRs to start with. Axiom 1 has its meaning only if the FRs are defined as functions we want to control independently of each other. As far as we have experienced hitherto it is always possible to define FRs in this way and this is important for a rational development process. However, this requires special attention. It is very easy to set up FRs that are inconsistent in this way and of course this makes Axiom 1 meaningless which also makes the decision process inaccurate. We have found many misconceptions about axiomatic design based upon inconsistent definition of FRs.

There is also interesting research going on called *Emergent Synthesis*, where methods to develop products and processes when information about DPs, PVs and/or environment is incomplete [Ueda, 2001]. Ueda distinguish between three conditions:

- Information about product and environment is complete.
- Information about product is complete and information about environment is incomplete.
- Information about product and environment is incomplete.

Emergent synthesis is referring to methods to develop products and processes when information is incomplete. We are not going deeper into this problem here. We are rather claiming that it is worth striving at accurate information first in order to be able to make decisions on complete information following axiomatic principles. In other words, try to stay within case 1 above to start with! No doubt, there are many cases still where emergent synthesis is needed and useful. So, this interesting research is worth following.

4 WHY DO WE CONSIDER THE PRINCIPLES OF AXIOMATIC DESIGN TO BE RELEVANT AS A SCIENTIFIC BASE FOR INDUSTRIAL INNOVATION PROCESSES?

To be able to outline the analysis of axiomatic design we will start this section by exploring the fundamental principles for the development process, which is perhaps the most dominant sub-process in the innovation process.

The model in **Figure 3** shows the fundamental elements of the development processes. That is, the real world, the model world and the decision world. The model is a projection of the real world. The data collected in the model carries the information needed for the decision-making, in a given competence context. The decisions will, when carried out, give an effect in the real world.

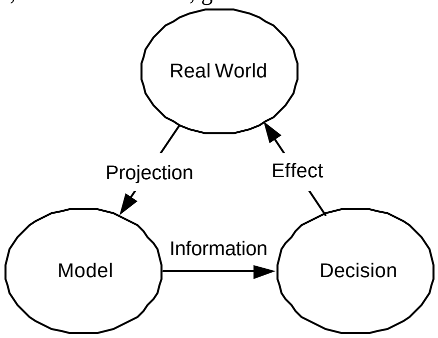

Figure 3: Fagerström's model concerning fundamental principles and relationships in development processes [Fagerström and Moestam Ahlström, 2001].

By defining the structure in **Figure 3**, we have formed a base for how the development process can be carried out in a logical way. With the guidance from this model the development process can be summed up in the following steps:

The first step in the development process is to define the goals for the process, including tolerances. This can be identified as the defining of function requirement, see Section 3. Furthermore, it is often necessary to identify the state from which the development process is initiated.

The second step is to consider what transformation that has to be done in order to get from the current state to the state where the goals are fulfilled. That is, what effects has to be accomplished in the real world to achieve the desired transformation.

The third step is to determine what decisions that have to be made, in order to achieve the desired effects.

The fourth step is to define the information needed to support a good decision-making. Good decisions, in the development process, are decisions that give an effect, which provides the shortest way from the current state to the state where the goals are fulfilled within tolerance. That is, a decision that consumes a minimum of energy and time. This is, naturally, directly according to Axiom 3 and Axiom 4.

The fifth step is to create a good model providing the right information. A good model could be described as a representation of something, where certain characteristics, which are important for the purpose of what the representation is going to be used for, are accentuated, while the other characteristics are left out [Føllesdal et al., 1993]. The purpose in this case is, naturally, to provide the right information to insure good decision-making.

However, just dealing with the logical way to carryout the development process is not enough when working in or with a development process. The human competence also has to be taken into consideration, see **Figure 4**.

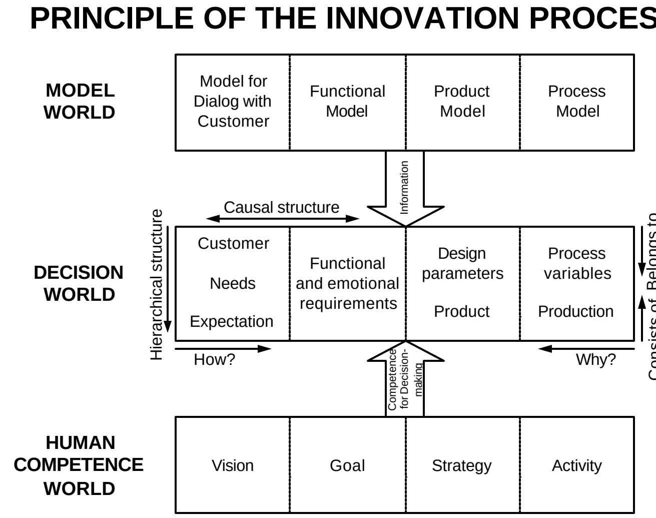

Figure 4. The innovation process can be understood as combining a decision world with the human competence world and the modelling world.

After examining the fundamental principles in the development process, it becomes clear that there are three worlds that are essential for a development process. These worlds are the model-, the decision- and the human competence world. These worlds are used, in the following sections, to do a thorough examination of the relevance of axiomatic designs as a scientific base for industrial innovation processes.

4.1 DECISION WORLD

Nam Suh proposes to see the design process as a mapping between four domains. This is principally a decision process where the objectives are defined from the needs and expectations of the stakeholders, primarily the customers but also the shareholders, the employees and the society.

A closer look at the logical nature of this process reveals two important orthogonal structures: the hierarchical structure vertically and the causal structure horizontally.

The hierarchical structure has to do with the hierarchical nature of the products. A product consists of components that consist of parts carrying features. This structure is the same in the functional, design and process domains and defined by the words *consists of* downwards and *belongs to* upwards.

The causal structure has to do with objectives and means and shows the connection between related positions in the hierarchical trees in adjacent domains. The words *how* and *why* are the guiding keys in this structure.

The existence of these two structures is the logical reason why an innovation process has to zigzag between the domains in the decisions about how to meet FRs with DPs realised from PVs. In other words Zigzagging is a logical necessity caused by the nature of products and processes.

The four axioms are valid decision criteria for the choice of the best alternative solution at each level in the hierarchical function-/design-/process variable-trees. This of course must be based also on engineering knowledge and creativity. This possibility to follow the logic of the innovation process is fostering creativity through the use of the rationality of the structures.

4.2 HUMAN COMPETENCE WORLD

The decisions have to be taken by humans cooperating in the innovation process. It is also necessary to develop the human part of the production system in its widest meaning, in parallel with and within the planning of the entire business process.

The qualitative part of this human system is very much equal to the competence of people involved. The ability/interest/desire to define goals and to make decisions is a prime core competence related to quality.

In this connection we have to understand competence as ability of each individual to act with correct actions at right time and with the right actions. This is naturally not easy. Therefore a competence management and a structured way of working in a competence strategy is needed.

A good way to help this development is to deal with concepts as *vision, goals, strategies, and activities* vertically in the company, **Figure 5.** This dialogue is a good instrument to create coherence in the understanding of strategies between the different organizational levels in the company [Kjellberg, A. 1999]. It is also useful and interesting to note that the concepts *vision, goal, strategy and activity* have the same conceptual meaning as *customer, function, design and process variable* in the decision world.

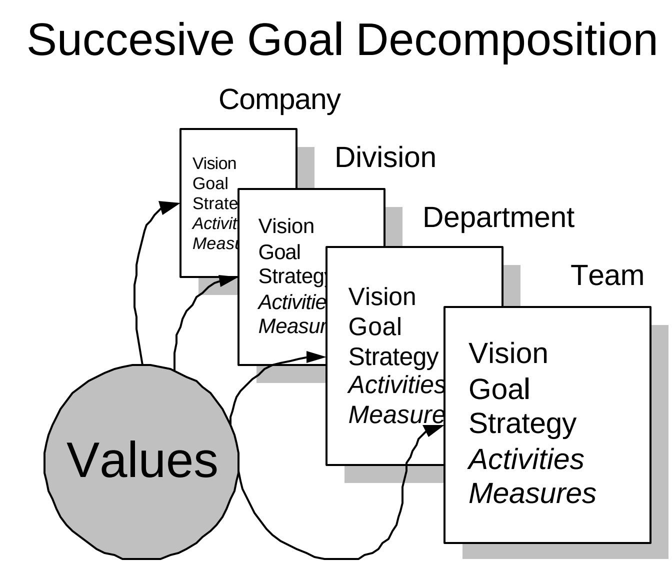

Figure 5. In order to create coherence between the different organisational levels in the company vision, goal, strategy and activities should be processed in a vertical dialogue within the company.

The decisions in the innovation process are defining the products and the processes within the business process and the business strategy.

In order to succeed the business strategy has to be accompanied with a competence strategy.

The competences needed for the new business-process around the new products have to be defined and developed within the innovation process. The current competences have to be defined. The new competences that are needed have to be defined. The differences, that is the competence gap, has to be defined and filled by different competence development activities, such as courses, mentorship, support from consultants and universities, alliances, etc. The strategies and activities for this have to be defined and planned, **Figure 6**. This is the Competence Management Process.

Some companies have involved all employees in so called competence workshops [Kjellberg, A. 1999] where competence gaps and activities to fill those gaps have been defined. This is a natural consequence of the vertical dialogue according to **Figure 5**. The gap defines the FRs on competence. The DPs have to be decided among possibilities such as those we listed above.

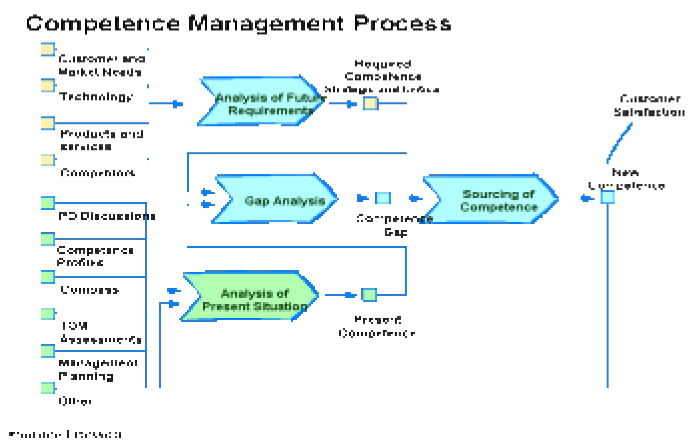

Figure 6, The competence management process must be part of the innovation process. Competence workshops can define competence gaps as a base for sourcing of competence. The gap is defining FRs on competence.

4.3 MODEL WORLD

The model world finally is really a part of the decision process and at the same time a necessary tool in the communication between humans and between humans and computers.

The models of products, parts and processes have to be created in parallel to the decisions in the decision world. The DPs have to be carried by features functioning to meet the FRs. Features are carried by parts, belonging to components that are assembled into products. The models are descriptions of products, components, parts and features capable of answering *what*-questions, **Figure 7**. In this way we can get a complete picture by handling *why* and *how* questions as well as *what* questions in a connected and consistent way.

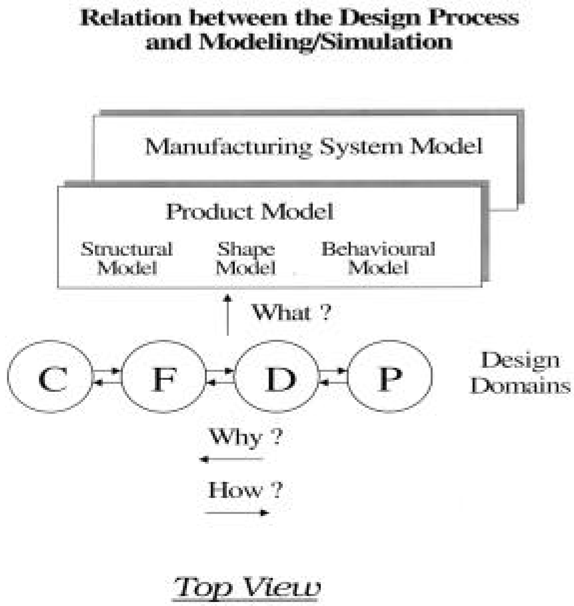

Figure 7, Modelling of products and processes has to be integrated with the decisions in the innovation process. Models are necessary means for the communication in the entire industrial process. The models also have to contain elements for the design decisions such as FRs, DPs and PVs.

A model is a tool for answering questions about something else, that is, the model is an information carrier. We are here considering different models for different purposes, such as showing shapes and dimensions, showing structural connections and showing behaviour in the production process as well as in use by the customer. Any model must be designed with purpose, viewpoint and detailing level in mind [Ross].

Today when agile production and business networks are developing between companies and when cooperation directly with customers is more important the possibilities to use modelling as a mean of communication and as a part of the decision process creates very promising possibilities. However, in order to succeed modelling must develop in coordination with the decision process and the human competence development.

5 CONCLUSIONS

In order to improve quality and productivity in industrial production we have to focus on competence to define goals worthwhile to achieve and to make decisions leading us to these objectives. The decisions must centralize around decisions about the products and processes to be designed.

The industrial innovation process has a certain logical structure. This has to be followed in the decision process. Zigzagging over four domains is a way to make use of this possibility.

If decisions can be based upon axiomatic theory the quality of the decisions will be improved. To be used in innovation processes four relevant axioms can be defined in relation to quality and productivity.

Human competence is of fundamental importance for the quality and productivity in industrial operations. This is especially true in the innovation process. For this reason a competence strategy must be combined with the business strategy. This strategy must deal with technological competence, business competence and social competence. The competence must also focus ability to define objectives and to make decisions meeting so defined objectives.

Modelling of products and processes is a powerful and necessary tool for documentation, communication, testing and validation. Development of models must evolve integrated with the decisions within the innovation process. There is a rich world of possibilities to model products and processes available to be used.

We think that the possibilities we have analysed and presented in this paper are worth considering for companies aiming at highest possible quality and productivity. The potential of this is not fully explored by many companies. A new way of thinking is necessary to develop.

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