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PRODUCTIVITY, QUALITY AND DECISION THEORY BASED UPON AXIOMATIC DESIGN

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ABSTRACT

The motto of the World Confederation of Productivity Science ”Wealth, Prosperity and Peace through Productivity” is an important true statement that is important fully to understand. However, it is also an important imperative to everybody in politics, civil services as well as in industry. Especially in manufacturing industries which have a direct effect on the wealth production, as it creates the tools we need in our daily life, this imperative is evident and very important. Studies have also shown a direct correlation between investment level in a country and the increase in labor productivity.
Wealth production also requires that we create and produce the products that are needed in order to improve the welfare. We understand this as quality, ”fitness for use”.

Today many products are complex systems that have to be designed in order to meet specific customer requirements on functionality, reliability and easy use. Market timing is also very important in order to meet the market windows, which especially for IT products are very short in time. Complexity must be combined with understandability and easy use through skillful engineering. Success requires today that the production processes and systems are designed integrated with the product design. We understand this as concurrent engineering.

In order to improve our skill in engineering design we have to understand the fundamental principles of good design and define and use a decision theory for development work. Such a theory can be defined with Axiomatic Design as a base. This can be further developed, taught and used in practice in order to improve productivity and quality in industrial product realization. We have also to distinguish between tools, methods and fundamental principles for engineering design. Products and processes also steadily include more knowledge through the use of information technology. The use of modeling techniques and information technology integrated with such a decision theory is important.

Keywords: design, axioms, productivity, quality, decisions

PRODUCTIVITY AND WELFARE

Productivity is a measure of effectivity in production. The word ”production” comes from Latin ”pro ducere”, which means ”bring or carry forward”. Productivity is of profound importance for our development of welfare. This is true for the government sector as well as for industrial operations.

Of course it is essential for the development of welfare, that what is produced also is needed. This means that the products must have features, functional as well as esthetical which satisfy people individually or in common. This is what we understand by quality.

It is also fundamentally important and a part of the welfare development that products and production processes not are causing any negative effects on people and on the natural environment. This is an important part of the quality requirements on products and processes.

Even sustainability is more easily met if we succeed to obtain and maintain high productivity in the production of goods and services.

Productivity and quality are inseparably connected. Effective production requires products with correct quality. Productive production of products with qualities that are expected, and that are not causing any bad side effects, simply constitutes our motor of welfare.

What is now required in order for us to be able to maintain and further develop this motor of welfare?

To start with we have to keep and further develop our ability, to develop products and production systems, where the central part is a productive refinement of raw material into products that are demanded and to do this in international cooperation and competition. The production system has to be considered the central part of the total business system.

To succeed we have to be skilled to utilize material technology, energy technology, information technology and control engineering within products and business systems. Productivity should be reached through smart work rather than hard work.. This means that we have to design and use efficient tools that can do the routinely and the energy consuming work for us. In an increasing degree we can then concentrate the human efforts on creative and innovative development work.

What are the basic requirements that have to be met in order to succeed?

- We need an effective educational system using the most effective learning methods - Problem Based Learning - which enhances individual learning abilities. Such an educational system would also stimulate creativity and entrepreneurship.
- We also need an effective and systematic Competence Management process. To create motivation at work, stimulating people to engagement, responsibility and entrepreneurship and gives opportunities for competence development at work, is the top challenge for modern vitalized manufacturing systems.
- .Furthermore we need a Decision Theory for development work, which improves our ability to define targets and to develop products and business systems that are meeting these targets with precision, functionally and right in time and place.

It is within our reach to succeed with this. The global cooperation between Universities and Industries that has been developing lately supported by governments and international programs are steps in the right direction.

Work productivity and capital productivity in combination with profitability have to be obtained through sustainable investments <Nicolin, C. 1980> in competence, products and production systems. This has to be part of a revitalized business strategy; the continuos improvement of Conscious Manufacturing <Hådeby, H. Kjellberg, A. Sohlenius, G. 1994>.

WEALTH PRODUCTION THROUGH MANUFACTURING

As already said, increased wealth requires that we succeed to develop products with functions meeting the needs of customers. This is, however, not enough. We have also to be able to produce them, so that the products really are meeting the requirements reliably during a long lifetime. They have to be delivered when they are needed and the prize has to be possible for the customers to pay. We have also to consider the whole product life cycle already in design in order to meet the needs for environmental sustainability.

Free markets and competition between companies in order to meet these requirements in the best way stimulates quality and productivity and are good ways to use manufacturing in order to create wealth.

Concurrent development of products and manufacturing systems in a direct dialog with customers in the market places is required in order to obtain a good customer satisfaction. <Sohlenius G. 1992>

Strategic alliances between companies with complementary capabilities, are being developed, where companies are cooperating in design as well as in production. This is a main part of what we call Agile Manufacturing. This cooperation is important in order to obtain the best quality and productivity. This requires integrated cooperation with partners already at the design stage.

This development, however, also makes products as well as manufacturing systems increasingly more complex <Sohlenius G 1997b>.To make complex systems reliable and easy to use is a serious challenge to engineering. We have to improve product design and manufacturing system design through improved methods based upon fundamental and solid principles.

Axiomatic design, Robust design and the Theory of Inventive Problem Solving contain basic principles that are improving creativity, productivity and quality if they are known and used. <Suh, N. P. 1990><Phadke, M. S. 1989><Altshuler, G. S. 1988>

Conceptual design, Parameter design and Tolerance design are logical important phases in the product realization process. Documentation and testing by using computerized modeling and simulation have to be integrated in the design process in order to improve productivity, quality and learning.

THE PRODUCT REALIZATION PROCESS

The product realization process can be studied and described from at least four different perspectives;

1. The Product Realization Process itself
2. The Products and Processes to be Designed
3. Modeling of the Products and Processes to be designed
4. How to Organize, Cooperate and Lead the work.

The Design of the Manufacturing System is the central part of what I here mean by ”Processes to be Designed”.

I will in this paper be focusing the fundamental principles to make Decisions about the Products and Processes to be Designed.

In order to do this, however, I have to consider the process first. In **figure1** this is shown in three SADT blocks;

1. Develop Product and Production.
2. Create Process Plan.
3. Produce product.

This figure is showing how input, output, control, resources and activities are related in the realization of the product. The work is in each company steadily improved through daily contributions in all steps. It is also improved from innovations where new generations of products and manufacturing systems are realized. For each generation of products the manufacturing system has to be redesigned or reengineered in order to meet new requirements.

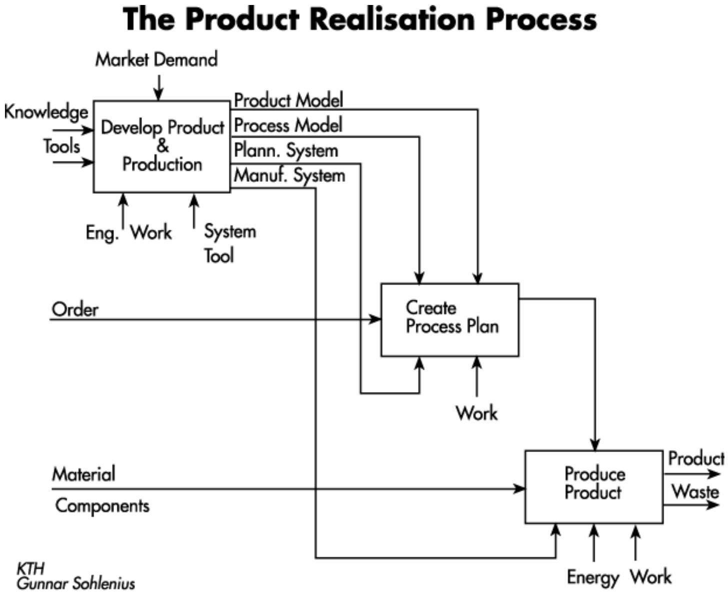

Figure 1 The manufacturing system consists of three subsystems, the Manufacturing Production System, the Data Production System and the Innovation Production System

FUNDAMENTAL PRINCIPLES OF CONCEPTUAL DESIGN In general, we use to distinguish between Detailed and Conceptual design. In Detailed design there is a rich set of fundamental theories, axioms and principles available, that are learnt in engineering education and used in practice. This is known as science for engineering and is based on natural sciences, mathematics and includes applied mechanics, solid mechanics, control theory, thermodynamics, machine elements, material-processing technology, computer science etc.

In Conceptual design, however, we lack fundamental principles. In order to be able to design products and manufacturing systems concurrently we need domain independent principles for conceptual design of products and manufacturing systems.<Holmstedt, P.1999>.

It is also importent to observe that In engineering design very often all aids ranging from theories and axioms to software systems, for instance cad/cam systems are considered as tools. This is understandable but not desirable as it makes our education and discussions less precise.

In the hardware domain this confusion is not occurring at all. 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 in a straight hit. In order to be able to succeed you have to know the method and you have also to exercise in order to obtain enough silent knowledge 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 that the theory behind this process is the following: 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 in a straight hit transferred with minor loss to the nail so that the nail 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 theories behind.

It is important to be equally specific in dealing with tools, methods and theories in engineering design. It is important here to develop methods and tools from fundamental principles validated in accurate research efforts. It is the competent use of such principles in design that can guarantee products meeting the expectations of the customers.

Design methods and design tools can be different but the designer using the tools and methods must know and guarantee that he is using fundamental principles in the tools and methods that in an efficient way lead to a product- and process- design meeting te requirements and satisfying the customers. In practice the engineers have to be unconstrained in the choice of tools and methods but have to know that the fundamental principles that are behind are leading to good products.

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.

In this paper my focus is on the fundamental principles rather than on tools and methods.

Axiomatic Design <Suh N. P. 1990>, Robust Design proposed by G. Taguchi <Phadke M. S. 1989> and the Theory of Inventive Problem Solving <Altshuller G. S. 1988> are together covering a collection of fundamental principles that are important to know and follow in the design of products and manufacturing systems, primarily in the conceptual phase. See **appendix 1, 2 and 3**. Based upon these principles different methods and tools for Engineering Design can be developed. The principles of Axiomatic Design are the most holistic ones that are giving us a possibility to describe a road map of principles upon which also the other sets of principles can be addressed <Nordlund M.1996>. Such a road map covering product and manufacturing system concurrent design is shown in **figure 2** <Sohlenius G. 1997a>.

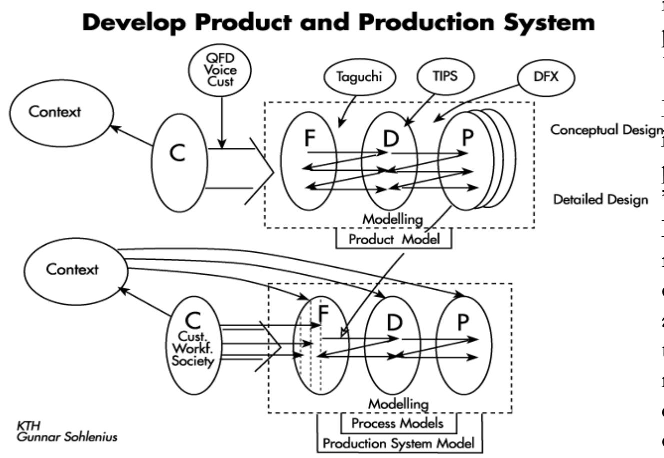

Figure 2 Road map for concurrent product and manufacturing system design.

The voice of the customer as to the Quality Function Deployment method <Clausing D. 1994> is describing how functional requirements can be captured from dialogues with the customers. The contribution by Clausing gives us an idea about how to define the principles necessary to understand in order to define an accurate set of functional requirements meeting the needs of a defined set of customers. Such principles may also be useful in order to define a market segment for functions that are possible to obtain from a product possible to develop and to produce.

The Theory of inventive problem solving is defining principles to be used in the creative work in order to find design parameters meeting agreed functional requirements.

Robust design and axiomatic design are complementary. Axiomatic design contains powerful principles of structuring the design, lacking in robust design. Robust design contains powerful principles to tune the design parameters, in order to meet the functional requirements in a robust way, lacking in axiomatic design.

Technical contradictions are often encountered in the design domain. The nature of a contradiction is that another function is degrading or a not desired function is developing when we are improving a desired function. From TIPS we learn that such contradictions are opportunities for innovations.

The design parameters also have to be chosen under the constraint of processes chosen on the next higher level in the process domain. The Design for Manufacturing and Assembly method proposed by Boothroyd and Dewhurst is an excellent example of principles useful in this connection.

Appendix 1, 2 and 3 are listing the fundamental principles behind Axiomatic design, Robust design and TIPS. These descriptions are different from available presentation of the methods in literature just because here just the principles behind them are listed.

This article is meant to be visionary and point at possibilities rather than present obtained results. Additional results are presented in <Yien J. T. S. 1998>, <Nordlund, M. 1996>,<Cochran, D. 1996> and <Engelhardt, F. 1998>.

MODELING IN PRODUCT REALIZATION Any cooperation in design or process control requires models of the products and processes to be designed or controlled. The principle behind "model" is the following: a model M is a model of an object O if M can answer questions about O. .A model therefore is to be regarded as a tool for answering questions about the object for cooperation and/or control. Models of products and processes are of fundamental importance in product realization. Seen as tools for answering questions about products and processes, the models have to be designed meeting the functional requirements defined from information needed in further cooperation and control within the product realization process.

As computers are used for modeling, very rich models can be developed. The accuracy of the information from the model is crucial for the quality of the result. The man - model interface as well as interfaces between models and technical systems, such as NC controllers and systems for planning and routing, are of fundamental importance for the efficiency. There is a rich world of modelers developed in CAD/CAM systems and systems for virtual reality. A model can be regarded as virtual reality, if the richness in the interface is very high, the answers are as rich and versatile as if they came from the real object. Models, especially on a Virtual Reality level, stimulate holistic understanding and improves by that, quality and productivity in engineering. The pedagogic effect of the man - model interface <Kjellberg, A. 1996> as well as standards for data interchange between computer systems, such as STEP <Kjellberg, T. Bohlin, M. 1996> is of great importance in the design of the models.

The modeling of the product and the manufacturing system is an important part of the product realization. According to the first principle of axiomatic design the design is detailed through zigzagging between the Function, Design and Process domains, **Figure 2**, answering the questions "why" and "how". In the design also the question "what" has to be answered and this is the role of the part-, product- and process- models. Therefore the modeling has to be integrated in the design process.

The modeling has to be done in parallel to the detailing of the design through zigzagging over the domains. **Figure 3,** where the domains are shown from the top is principally showing this relation of modeling to the axiomatic design process. The questions "why", "how" and "what" relates the domains and models to each other in the product realization process.

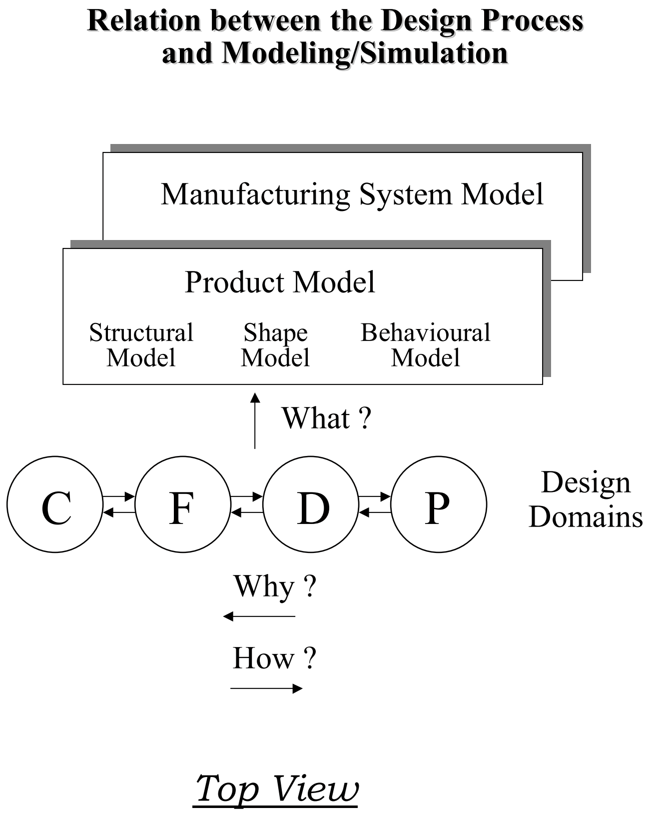

Figure 3 The relation between the decision process and modeling in design. The questions "why", "how" and "what" relates the design domains and models to each other.

EXPERIENCES AND CONCLUSIONS.

Practical experiences from the use of these principles are evolving in cooperation between companies such as ABB, Ericsson, Saab <Nordlund, M. 1996>, Tetrapak and Ford <Engelhardt, F. 1998> in cooperation with MIT, HKUST and KTH. The results are showing that the productivity and quality is improved by following these fundamental principles in the realization of products.

QUALITY, PRODUCTIVITY AND DECISION - THEORY FOR ENGINEERING DESIGN

Design of products and business processes is a decision process. To obtain skill in realizing products we therefore need to obtain skill in defining targets and to make decisions. For this we need target oriented decision criteria. See the decision matrix in **figure 4**.

We all know that quality, cost and time are important practical measures for industrial competitiveness. From DR Juran we have learnt that quality should be interpreted as "fitness for use". This means that we have to know the expectations of the customers in order to be able to make decisions on quality. The customers expect the products to meet their functional requirements. The ability to define those functional requirement (FRs) correctly therefore is a necessary precondition in order to succeed and to be able to deal with quality.

QUALITY

The FRs have to be defined in a dialogue with customers in the marketplaces and defined as the minimal necessary functions of the product including allowed deviations from target values, that is to say tolerances. In the design the term quality means that we have to see to that the product is meeting those defined FRs within agreed tolerances.

Decision criteria for this is defined by Nam P. Suh in terms of axiom 1 (maintain the independence of the FRs in the selection of design parameters, DPs) and axiom 2 (minimize the information content). If we have defined the FRs correctly they define requirements that the customers need to control individually. The information content as to axiom 2 is the sum of the logarithms of the inverse of the probabilities to meet each of the FRs within their tolerances. So, therefore the practical meaning of axiom 2 is the following: Among alternative designs, the one with highest probability to meet the FRs within tolerances, is the best.

Axiom 1 defines a decision criterion for functionality and axiom 2 defines a decision criterion for success. Axiom 1 and axiom 2 therefore are the correct and useful decision criteria for quality.

PRODUCTIVITY

Now, how about productivity? In order to be able to understand this conceptually, let us take a helicopter view on product realization and ask ourselves: What are we in essence doing when we realize products? Obviously, we are extracting materials, such as minerals, chemicals and biologic materials from nature and process them into products that we use in order to improve our life. We are not paying for the natural resources as such. We are taking them for free resources. We process the material with the use of energy into products. In order to succeed we have to control the energy with information. To acquire and develop this information into the information we need in order to define the products and to control the processing energy, we have to do work also requiring 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 the overall observation that can be concluded in the following way:

In order to realize poducts we extract materials from nature and process this material 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 put in, in order to design and produce the products. Of course, this measure is, from a scientific point of view, a very inaccurate measure, as it is distorted from market prizing, taxes and interest rates. 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.

DECISIONS AND CRITERIONS IN DEVELOPMENT WORK

DECISION	CRITERION	PRINCIPLE	EFFECT
Functionality	Functional independence	Axiom 1	Quality
Certainty	Max Probability	Axiom 2	Quality
Robustness	Min Variance Sensitivit.	Rob. Design	Quality
Effort	Minimal energy	Cost	Productivity
Access	Shortest time	Time estimate	Productivity

Figure 4 Decision theory for Engineering Design.

After quality therefore energy requirement, which might be measured as cost, is the next decision criterion, that has to be used in engineering design. (engineering design includes process design to produce the products). We could formally express this also as an axiom 3: Minimize energy in the selection of design parameters that are meeting the functional requirements. Cost can be used as a measure here. This 3rd axiom is a productivity axiom expressed as cost to meet a defined target, in this case defined in terms of quality as above.

In general, productivity is related to the target defined, regardless if it is the most effective target or not. Effectivity requires, however, correct target in this case quality defined by axiom 1 and 2 together with axiom 3.

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 above, cost for energy as well. Efficiency, verkningsgrad in swedish, should be expressed in % and defines the fraction of the input that is the useful output.

((Input - waste)*100)/ input.

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 effect that is used (energy per unit of time) is playing a major role. This means that we need a decision criterion on an axiomatic level for this either an axiom 3 measuring effect rather than energy or an axiom 4 as a decision criterion for time. An axiom for time seems to be most practical; Axiom 4: Minimize time in the selection of DPs meeting the FRs according to axiom 1 and 2. In principle those four decision criteria expressed as axiom 1 - 4 can guide decisions in any development work and especially in engineering design. The order between decision 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.

They decisions related to quality have to be taken dealing with functionality and certainty. The decisions related to productivity have to be taken afterwards. Axiom 1 must preceed 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 could also be defined as constraints (maximum allowed cost or time). In this case they are active in the selection of the acceptable alternative solutions, to start with, 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 build in conservativity. We are satisfied if we just meet the constraints. Therefore it would be better to use these parameters as decision principles, **figure 4.**

Figure 5 is a further development of **figure 3** showing a road - map for concurrent design of product and business process. In zig - zagging down in the design process the decisions can be improved by using these decision criteria.

The knowledge and competence of people is crucial, together with the tools and systems they are employed to manage in order to meet this challenge. The Decision Theory we are proposing here, will have an effect only if it is combined with a correct and competent management.

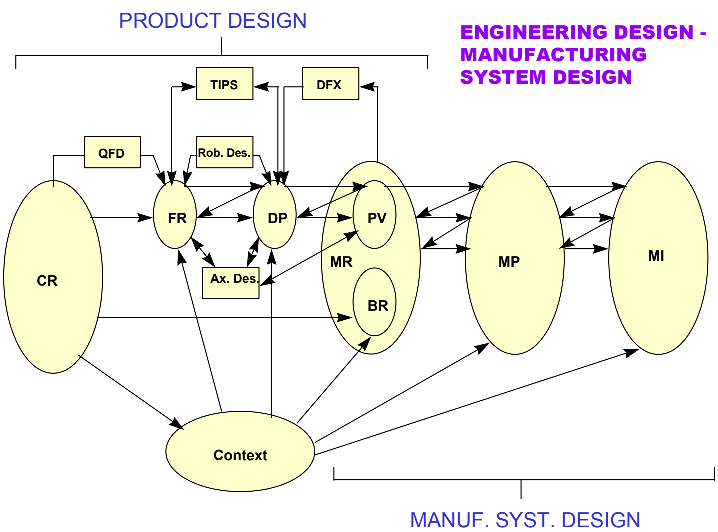

Figure 5 Roadmap for concurrent product and business process design.

CONCLUSIONS

In conclusion: Quality means Functionality verified with the use of ***Axiom 1*** and Probability to meet the requirements within agreed tolerances verified with ***Axiom 2***. Productivity means to meet a defined target with low Energy consumption (Cost) verified with ***Axiom 3*** proposed here and short Time verified with ***Axiom 4*** proposed here. To meet the Functional Reguirements with high Probability at low Energy and short Time is Effective(verkningsfullt in Swedish). Quality and Productivity together defines *Effectivity*. Efficiency (verkningsgrad in Swedish), is a measure of a process and defines useful Output in relation to Input. The output is understood as input minus waste.
This is meant to be an outline of a decision theory for development work based and expanded upon from fundamental principles found in Axiomatic Design, Robust Design and The Theory of Inventive Problem Solving.

FINAL REMARKS

Industrial Manufacturing has an important role as our main motor of welfare. Productivity and quality is required in order to succeed. To extend our possibilities to contribute to Wealth, Prosperity and Peace through Productivity in manufacturing we need to focus on Innovative Competence, ability to define customer oriented targets and ability to make correct decisions together with ability to understand, develop and use advanced technologies in tools and products. In this connection a decision theory based upon fundamental principles is of great importance. Such a theory can obviously be developed and used in order to obtain good quality and high productivity.

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Appendix 1

FUNDAMENTALS OF AXIOMATIC DESIGN

Design is a mapping across four domains; Customer-, Function-, Design-, and Process-domain.

The relation between the domains is defined by the questions “why?” and “how?”.

The hierarchical design tree is congruent with the function tree and the process tree.

The dependence between the domains must be considered by zig-zagging over the domains when detailing the design.

The design-parameters have to be chosen so that the functions of the product are as independent as possible from each other.

The design-parameters have to be chosen so that the probability of meeting all the functional requirements is maximized

Appendix 2

FUNDAMENTALS OF ROBUST DESIGN.

The functioning of a product is characterized by signal factors, SF, and response factors, RF, influenced by control factors, CF, and noise factors, NF.

In a robust product the RF s are accurately meeting their target values under the control of CF s independent of NF s.

The robustness of a product can be increased through parameter design and tolerance design.

A quality loss function is used to define the cost occurring when RF s deviate from target values.

Parameter design through choice of operating values using nonlinearities increase robustness without increasing cost.

Experiments using prepared orthogonal arrays is used to find parameter values increasing robustness.

Tolerance design through additional design, increase robustness with cost increase.

Appendix3

FUNDAMENTALS OF THE THEORY OF INVENTIVE PROBLEM SOLVING.

The purpose of a product is its functions. If the functions can be obtained without the product, the product is not needed.

The laws of evolution.

Technical conflicts have to be solved through innovation, not through optimization, compromise or negotiation.

Separation in time, space or through inner structure are the main methods to relax a conflict.

40 additional inventive principles are available.

1350 physical, geometrical and chemical phenomena and effects are available.

39 conflicting parameters and associated innovative principles used to relax each conflict are presented to stimulate creativity.