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ON COMPLEXITY AND UNCERTAINTY IN A MANUFACTURING SYSTEM DESIGN PROCESS

Marcus Bjelkemyr
mbj@iip.kth.se
KTH – Royal Institute of Technology
Dept. of Production Engineering
S-100 44 Stockholm,
SWEDEN

Prof. Bengt Lindberg
bli@iip.kth.se
KTH – Royal Institute of Technology
Dept. of Production Engineering
S-100 44 Stockholm,
SWEDEN

ABSTRACT

In order to be competitive today and in the future, an organization must be aware of how their products and the correlating life cycle systems affect each other. This is particularly important in the design of a manufacturing system, where the development should be done concurrently with the product to reduce cost and time, and to increase quality.

This design of products and their corresponding life-cycle systems is a complex and complicated task that is dependant of several multidisciplinary areas, for example technical, economical, social and managerial. Therefore, the correlation between the developed manufacturing system and the demands from the product and from the operations strategy is established under great uncertainty.

In this paper, the connections between different engineering design tools that can be used as support in the manufacturing system design (MSD) process, within the context of two MSD-methodologies, *Design for Six Sigma* and KTH-IPM, are discussed. Also, the paper elaborates the relationship between the MSD-process and the development process of a MSD-tool.

Next, the MSD-process is broken down in order to be evaluated on performance and dependability. The performance of the MSD-process can be evaluated using the concept *logical depth*. The dependability of a MSD-process can be evaluated with the notion of uncertainty as presented by Suh [2003] and Lee [2003].

The purpose of this paper is to position manufacturing system design (MSD) with regard to terms like complexity and uncertainty in order make MSD more efficient by improving the MSD-process. The aim of this research is to further develop and refine tools for MSD.

The research has mainly been conducted through literature studies, but also through observations of MSD-student projects and prior MSD case studies. The research is a further development of the research presented by Aganovic et al. [2003], Aganovic and Bjelkemyr [2004], and Aganovic [2004] which present how different engineering design tools can be combined in a manufacturing system design methodology.

Keywords: Manufacturing system design, complexity, uncertainty, concurrent engineering, engineering design theories.

1 INTRODUCTION

1.1 FUTURE NEEDS

The Swedish "Technology Foresight" program for future studies has pointed out five key areas that are and will be important for the future in production: customers crave individualized products, individuals and companies live locally but work and compete globally., production and product development is done in networks, 'function retailing' enables a closed flow of resources, and that the intellectual capital is the most important mean of competition [Teknisk Framsyn, 2003]. Together with current tendencies like e.g. shorter time-to-market, faster personnel turn-over, and increased demands on short term profit; these trends are the requirements that organizations within production must adhere to. In order to do that, organization must increase their knowledge of what they want to do and for whom, how to do it, with which resources and which stake holders, and how they can do it with the right *quality*, *speed*, *flexibility* and *dependability*, and to the lowest *cost*.

1.2 CONCURRENT ENGINEERING & DESIGN TOOLS

In order to excel in product and manufacturing system development and to give the customers what they want when they want it, the development of a product and its lifecycle systems must be done concurrently. Concurrent engineering does not only shorten the development time, but also increases quality and productivity, which is obtained by making the right decisions from the beginning [Sohlenius, 2000]. This way of working requires knowledge about both how the product and the manufacturing system is developed; further, it also requires knowledge of how and when the product affects the manufacturing system and vice versa. Since the development process is often built up by numerous interconnected tasks to be executed by many different people or roles, a common work process with standardized methods and expressions are necessary for it to be efficient over time. The performance and dependability of MSD is discussed in Section 3.

1.3 AIM AND DELIMITATION

The purpose of this paper is to position manufacturing system design (MSD) regarding terms like complexity and uncertainty in order to be able to improve the MSD-process. The aim of this research is to further develop and refine a tool for MSD. The development of a MSD-process may be expressed in axiomatic design terms as:

- **Functional requirement (FR)**: Facilitate the development of a model of a manufacturing system for an electromechanical product.
- **Design parameter (DP)**: A MSD-tool.
- **Process variable (PV):** Research in the area of manufacturing system design, e.g. literature studies, case studies, et cetera.

This FR-DP-PV for the development of a MSD-process coupling is not to be confused with a specific MSD-project, which may be described as:

- **Functional requirement (FR)**: Reconcile the organization's operations strategy and the functional requirements imposed by a product design into a manufacturing system.
- **Design parameter (DP)**: A model of a manufacturing system and its corresponding product(s).
- **Process variable (PV):** MSD-tool.

This distinction is important to consider when improvements of the process are to be made.

Even though the development process should be done concurrently, the studies made have focused on a development process where an *open product model* [Fagerström et. al., 2002] has already been developed, i.e. there is an existing product model with non-fixed design parameters that answer to functional requirements, which answer to customer needs and non-production constraints.

2 METHOD

This research is based on a research model presented by Fagerström et al. [2002] and Aganovic [2004]. It is a general model that shows the relationship between elements of the scientific theory-building process in scientific research, and it consists of the elements below, also pictured in Figure 1.

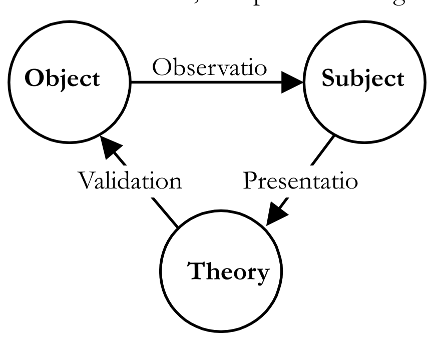

Figure 1. Model of research, Fagerström et al. [2002]

Object – physical things, processes and behaviors observed in the real world. In this paper mainly processes and tools for manufacturing system design (MSD), books and articles on complexity, and projects with students in MSD-projects.

Subject – the researchers who perform the observation, analyze the data and present the theory.

Theory – the result of the research activity that answers the research question. In this paper: A theory for evaluating the MSD-process.

Observation – the collection of data regarding the object. In this paper: prior case studies, student MSD-projects and literature studies on engineering design tools, MSD-tools, and on complexity and uncertainty.

Presentation – a short description of the observed objects, and the result of the data analysis performed by the subjects.

Validation – securing of consistency and correlation between the presented theory and observed relevant objects. In this paper the theory has only been validated regarding its correspondence with the studied objects.

3 RESULTS

3.1 OBSERVATION OF THE RESEARCH OBJECTS: FRAME OF REFERENCE

The theory that will be presented on the following pages is based on literature studies and case studies previously conducted by the authors (i.e. the subjects). How different engineering design tools can be connected to fully cover the whole MSD-process has been presented by Aganovic et al. [2003] and Aganovic [2004]. The use of comprehensive MSD-tools that incorporate engineering design tools has been presented by Aganovic and Bjelkemyr [2004], Aganovic [2004], and Yang and El-Haik [2003].

Theories on complexity and/or uncertainty have, amongst others, been presented by Lee [2003], Suh [2003], Nørretranders [1999], Bennett [1988].

3.2 PRESENTATION OF THE THEORY: A FRAMEWORK FOR MSD-EVALUATION

Engineering Design Theories and Tools

There are many different engineering design tools, methods, and theories that aid description and improvement of a product and its life cycle systems, and also the relationship between these. Engineering design theories describe how models of the product and the correlating systems should be structured. Such a product model structure is a decomposition of the product design, which represents the intent with the design as well as the design history. By making controlled and well-documented design decomposition, it is possible to trace the design decisions made by the developers. Although most engineering design theories are focused on product design, the manufacturing system can also be regarded as a product of its own, which makes the theories applicable also to manufacturing system development [Aganovic et al., 2003].

The model developed is based on Theory of Domains (ToD) for qualitative parameters and Axiomatic Design (AxD) for quantitative parameters. These two are closely interconnected and filled with more information from numerous interrelated engineering design methods and tools, e.g. IDEF3, IDEFØ, Process Flow Charts (PFC), Relationship and precedence diagrams (layout), Discrete Event Simulation (DES), Method-Time-Measurement (MTM), Computer Aided Manufacturing (CAM), Computer Aided Design (CAD), Design of Experiments

(DoE), and Design for Manufacturing and Assembly (DFMA). The connections between engineering design tools are shown in Figure 2 which is adapted from Aganovic [2004].

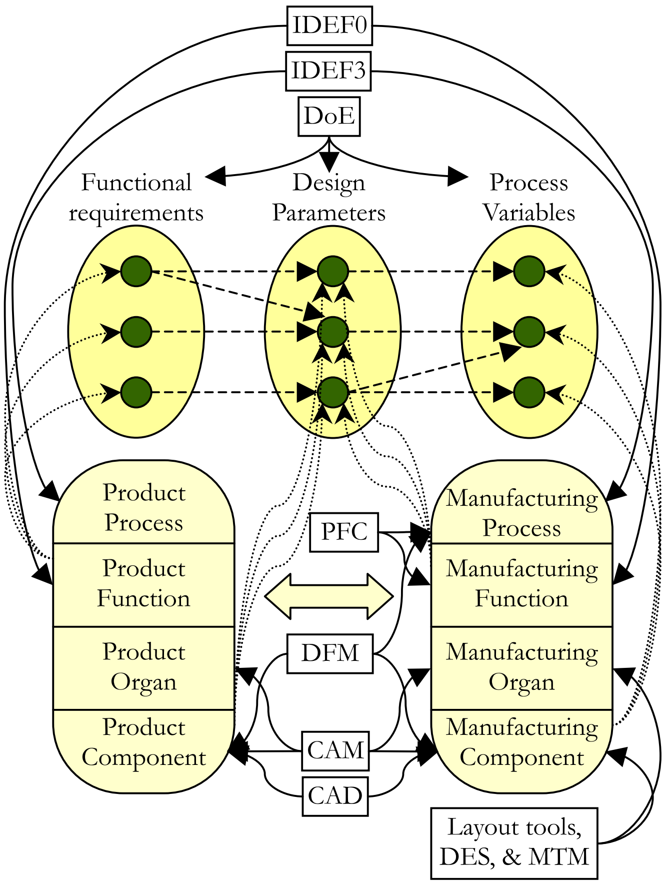

Figure 2. Description of how different engineering design tools are connected [adapted from Aganovic 2004].

Manufacturing System Design Methodology

In order to industrialize the use of engineering design tools in manufacturing system design (MSD), they must be ordered in a complete and manageable framework that aids the control of MSD-projects. Two MSD-tools, KTH-IPM and *Design for Six Sigma*, are presented bellow. They have been developed independently, but both aim to facilitate the MSD-process in a similar way.

A framework for MSD has been presented by Aganovic and Bjelkemyr [2004] and Aganovic [2004]; and it has also been implemented as an internet application – KTH-IPM (see www.iip.kth.se/~dag/teaching/tis0304/kthipm for a detailed description).

In KTH-IPM the MSD-process is divided into five stages (Preparation, Concept design, System design, Detailed design, and Completion), which are described in terms of their inputs, outputs, and clearly defined activities that need to be executed in order to transform inputs to outputs. The stages are separated by gates in order for the management to regularly check that the results correlate with the operations strategy. The project model also provides documentation templates. Further, the developed information about the project, the product, the manufacturing system, and how they correlate is also collected in a PDM-system. The engineering design methods and tools presented in Figure 1 are utilized at different times during the MSD-project.

The KTH-IPM has been tested in a total of seven industrial projects that have been executed by students from the Department of Production Engineering at KTH and engineering staff from small and middle sized Swedish companies between January and May in 2003 (2 projects) and 2004 (5 projects). During this period, every project engaged 5-7 students that are working half time. The starting point is an assignment specification, an open product model, and business data.

A similar stage-gate MSD-process framework is presented by Yang and El-Haik [2003] as *Design for Six Sigma* (DFSS), in which the aim is to proactively improve the product to improve quality and reduce cost in production. Yang and El-Haik have, similar to KTH-IPM, divided the MSD-process into four phases to aid the development (Identify requirements, Characterize the design, Optimize the design, and Verify the design). These phases are in turn decomposed into specific steps, where different engineering design tools like e.g. QFD, Axiomatic design, TRIZ, Design for X, FMEA, Taguchi's experimental design and robust parameter design, and tolerance design, are utilized.

These phases and steps are positioned in a DFSS project algorithm, which step-by-step shows what should be done with which tools. The algorithm also proposes both tollgates between the phases in order for the management to regularly check the correlation to the operations strategy, and also an iterative work method in which the results from each step is validated against the objectives in the project.

Critical Segments in MSD

To properly analyze how the MSD-process can be improved with regard to performance and dependability, the process can be divided into: establish functional requirements for the manufacturing system that is to be developed, facilitate reaching the functional requirements, and facilitate reconfiguration of the designed manufacturing system. Performance is in this paper defined as how well the primary characteristics are fulfilled; dependability is defined as with what consistency the primary characteristics are fulfilled, i.e. that what is promised is delivered.

Establishment of functional requirements requires knowing what the customers require and what you are able to deliver. An organization's success is dependent on how well it manages this reconciliation of the organization's operations resources and the market's requirements, which is why an organization must carefully and thoroughly develop and follow their operations strategy. This strategic reconciliation can be evaluated by defining the organization's resources within decision areas like *capacity*, *supply network*, *process technology*, and *development and organization*; and then evaluating each of these according to the performance objectives: *quality*, *speed*, *dependability*, *flexibility*, and *cost* [Slack and Lewis, 2002]. When developing a manufacturing system, the organization's strategy must be decomposed into more specific functional requirements on the manufacturing system, which both reflect the strategy for the finished manufacturing system and are easier to quantify and measure.

Fulfillment of the functional requirements requires that the MSD-project participants know what to do, how to do it and when. Since MSD is a very intricate process, even a simple process is difficult to master without engineering aids, regardless of how experiences the personnel is.

The process of developing a manufacturing system can be evaluated with the same performance objectives as for the finished manufacturing system. *Quality* is in the MSD-process mainly a measure of how well the developed manufacturing system corresponds to the functional requirements; but also that the process is traceable and improvable. *Dependability* shows the consistency of the development process, this parameter distinguishes structured processes from ad hoc processes that can hit the target but is more likely to miss. *Flexibility* is a measure of how well the development process adapts to changed conditions, i.e. requirements or resources are altered. This could for example be that a member quits the project group or that the initially determined product volume is increased. *Cost* and *speed* are basically measures of the deviance from a straight line between the initial conditions to the final; therefore they can be seen as a measurement of efficiency. Moreover, while high speed is not necessary optimal in the development process, cost should always be as low as possible.

Reconfiguration of the manufacturing system that was developed in a prior MSD-processes, and reuse of the developed information, are both imperative for an organization to be efficient in the long run. It is important to be able to predict what effects a change of the product has on both the manufacturing system and the product itself. Similarly, effects of manufacturing system changes must also be predictable. Consequently, it is not only the operations strategy and the open product model that are the prerequisites, in reconfiguration the constraints of the current manufacturing system must also be considered.

Reconfiguration and reuse are naturally also depending on *quality*, *speed*, *dependability*, *flexibility*, and *cost*.

Evaluation of MSD-performance

To be able to prove that a certain MSD-methodology is superior to another, the three critical segments discussed in the previous section must be measured and evaluated. The evaluation and comparison of the complex and complicated MSD-process is very difficult, partly because it is a mix of natural science, economics, social science and the humanities.

There are many different definitions of complexity; some of which have been discussed in Edmonds [1999], Lee [2003], Suh [2003] and Nørretranders [1999]. A usual way to measure complex entities is the *Algorithmic Information Complexity*, (or *Kolmogorov complexity*), which can be interpreted as the length of the shortest string of binary input that in a Turing machine can represent the measured entity. According to Nørretranders, this results in that a totally random string of symbols is more complex than a written text with the same number of symbols; that pure noise is more complex than a symphony, which may imply that an ad hoc manufacturing system development process is more complex than a well structured, thorough development process.

Therefore, the level of complexity must also consider the value of what is studied. According to Bennet [1995], "the value of a message is the amount of mathematical or other work plausibly done by its originator, which its receiver is saved from having to repeat". This value, which Bennet calls *logical depth*, is a measure of tings that the receiver could have figured out, but only through putting in substantial cost, time, and effort.

In MSD, the notion of *logical depth* can be exemplified by contrasting an ad-hoc MSD-process to a structured MSD-process, illustrated in Figure 3. In order to reach the same depth, considerably more resources must be invested in an ad-hoc MSD-process to reach the same result. This is valid, given that the MSD-project participants in the two cases start at the same knowledge and experience level, and that the end result is evaluated against the same functional requirements, i.e. that the total *logical depth* must be the same in both cases.

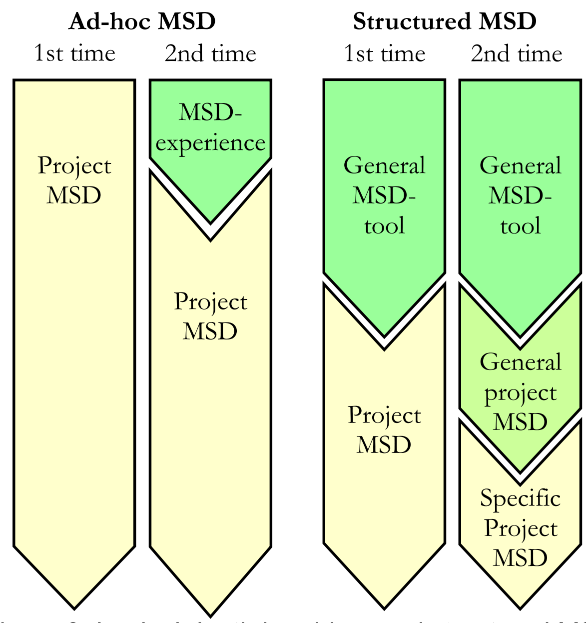

Figure 3. Logical depth in ad-hoc and structured MSD

In the first MSD-project in an ad-hoc setting all work must be executed by the project participants, including structuring of the project and development of the manufacturing system. The second time, the participants have somewhat learned how to execute a project, why the required work has decreased.

In the first MSD-project in a structured setting some of the required work has already been done by those who developed the MSD-tool, the project participants must here follow the pre-developed structure when developing the manufacturing system. The methods and tools in the general MSD-process must also be learnt, but since it requires less work to learn a tool than to obtain the information that is already included in the tools, this part is also more efficient. The second time the participants have gained some experience, but can also reuse some of the information that is general for the products, manufacturing system and projects in the organization. Consequently, the required total work has decreased. This is particularly apparent when a manufacturing system is reconfigured, because all the characteristics, correlations, and information on why something is done in a specific way are easily accessible.

Evaluation of MSD-dependability

The concept of *logical depth* shows the amount of work that has been put in and that someone else does not have to do in order for the finished result to be satisfactory, which affects the *quality*, *flexibility, speed*, and *cost* in the MSD-process, as defined in MSD-Methodology section. However, the dependability of the MSD-process, i.e. *dependability*, is not necessarily increased just because the required work is decreased; if the general MSD-procedure is outside the tolerance limits of its performance, the *dependability* (and also *quality*) is rather decreased. The likeliness that the desired functional requirements will be reached is though increased since the tools and methods used for guidance have already been verified.

In order for the functional requirements to be realized in a specific MSD-project, the dependability must be increased, i.e. the uncertainty must be decreased. In order to increase dependability in a system, uncertainty can be understood as the "uncertainty in understanding what it is we want to know or in achieving a functional requirement" [Suh, 2003; and Lee, 2003]. In a specific MSD-project this would translate to uncertainty in knowing how to reconcile the organization's operations strategy and the functional requirements of the product into a manufacturing system.

Further, to reduce uncertainty, Suh distinguishes four different types of uncertainty: time-independent real uncertainty, time-independent imaginary uncertainty, time-dependant combinatorial uncertainty and time-dependent periodic uncertainty.

In Figure 4, adapted from Suh [2003], some important aspects in determining the fulfillment of a FR are illustrated: the *design range* is the tolerance of the FR; the *system probability density function* is the performance of the system, and it identifies the *system range*; the *common range* is the intersection of the *design range* and the *system range*; the a*rea within common range* is the only time that the FR is satisfied; the *target* is the center of the *design range*; the *bias* is the difference between the *target* and the mean of the *system pdf*.

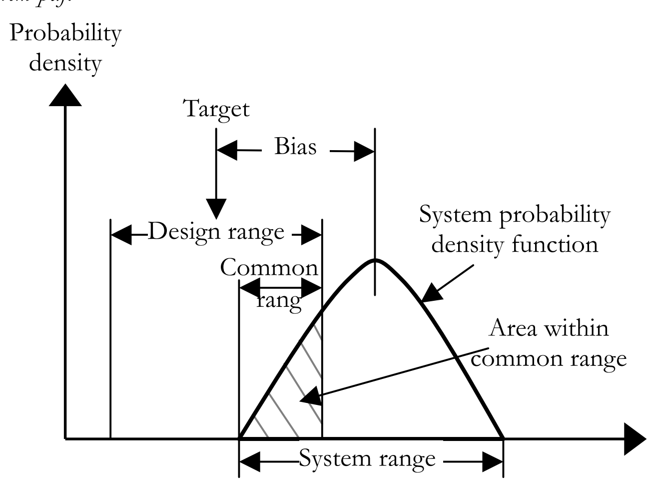

Figure 4. Design range, system range, common range, and system pdf for a FR [Suh, 2003].

Time-independent real uncertainty appears when at least some part of the *system range* is not overlapped by the *design range*, i.e. when the *system pdf* is not the same as the area within *common range*.

In MSD this means that, due to errors in the MSD-tool, the organization's operations strategy and the functional requirements of the product can not be translated into correct and relevant models of the manufacturing system that is developed. Consequently, this uncertainty must be reduced by those developing MSD-tools and engineering design theories.

Real uncertainty can be reduced if the MSD-tool is uncoupled or decoupled. If uncoupled, each tool within the complete MSD-tool can be adjusted and refined in order to improve the result. If decoupled, the sequence that the tools are used can be altered to minimize the uncertainty. If the MSD-tool is coupled, the uncertainty can also be reduced; however, it can only be reduced with regard to the whole tool, not with regard to individual tools, or the reduction of uncertainty can at least not be verified.

Time-independent imaginary uncertainty is due to the designer(s) lacking in knowledge and understanding, i.e. even though the *system range* and the *design range* are overlapping, the designer might not know how the systems work and consequently can not use it properly.

In MSD imaginary uncertainty occurs when the personnel in a specific MSD-project does not understand what to do and how to do it, or how things are connected or should be connected.

In order to minimize imaginary uncertainty the tools used within the MSD-tools must be understood by the project members. Further, if the tools are connected it must be clear how they are connected and what happens when parameters are changed. To achieve this, the competence of those working in MSD-projects must be increased. MSD-tools and the corresponding engineering design theories and tools should continuously be educated within the organizations. It is, however, of great importance that the MSD-process and aids are also educated to undergraduates in engineering programs that are somehow related to product development or manufacturing system development [Aganovic and Bjelkemyr, 2004]. This is imperative since the MSD is complex and uncertain to its nature, and therefore demands extensive time and effort to master.

Also, as in both KTH-IPM and DFSS, the MSD-process can be separated into smaller stages with gates where the developed models can be fixed, which decreases the amount of couplings and consequently the imaginary uncertainty.

Time-dependant combinatorial uncertainty is due to that the *system range* and/or the *design range* varies over time. Either the developed system is initially be within the *design rang*, but over time it changes and it gets increasingly difficult to satisfy the functional requirements; or, the functional requirements are shifting over time. If the FRs are shifting it is either because target values for FRs vary over time, or because set FR target values change over time [Lee, 2003]. In MSD, combinatorial uncertainty is mainly due to changes to the prerequisites, i.e. the product, the operations strategy, and in some cases also the current manufacturing system..

After a while, the models that were developed in the MSD-process do not represent the present conditions, and predictions on future changes become increasingly difficult.

Combinatorial uncertainty is reduced by making it periodical, by resetting the combinatorial uncertainty and thereby increasing the *common range*.

Time-dependent periodic uncertainty means that the *system range* or the *design range* periodically is adjusted to the other, thereby resetting the uncertainty that has developed over time..

In MSD it is the system range that has to be adjusted to the design range. In order to do that with a minimum amount of effort, the MSD-tool must clearly indicate the implications of changes of the design range.

4 CONCLUSIONS

The area of MSD is very important for manufacturing organizations in to be efficient and therefore competitive. The development and improvement of MSD-tools is very important to aid all kinds of manufacturers of electro and/or mechanical products. Consequently, it is also an important way to improve the competitiveness nationally.

The MSD-process can be divided into: establish functional requirements for the manufacturing system that is to be developed, facilitate reaching the functional requirements, and facilitate reconfiguration of the designed manufacturing system. The functional requirements can be evaluated with *quality*, *speed*, *flexibility*, *dependability*, and *cost*.

When evaluating the performance of different MSD-tools it is important to consider the amount of work that has to be done by the MSD-project personnel, and the amount of work that has been done by someone else and then reused in the MSD-project. These two combined yield the *logical depth* of the project outcome.

Because a MSD-project usually requires a lot of work by a lot of personnel, and because the correspondence between the operations strategy and the developed manufacturing system determine the profitability over a long period of time; there is a great need to avoid uncertainty in the MSD-process.

Real uncertainty can be reduced improving the MSD-tool, i.e. by aligning the *system range* with the *design range*, which is achieved by research on and development of MSD.

Imaginary uncertainty is reduced by educating the MSD-personnel on specific tools, how they are related, and what happens when a parameter is changed. It can also be reduced by fixing parameters through tollgates in the MSD-process.

Combinatorial uncertainty, which in MSD is due to changed demands, can be reduced by periodically resetting the system so that it correlates with the *design range*.

Future work: should be focused on both increasing the depth by increasing quality and adding additional functionality to the MSD-tools, and on reducing the uncertainty in the MSD-process. To achieve the latter, the couplings in and between the MSD sub processes must be analyzed and reduced, the interface between the MSD-tool and the users must be improved, and research must be done on how to transfer work that is currently done by the project members in to the MSD-tool. Also, to be efficient over time, further research must be done on facilitating reuse of information and reconfiguration of the manufacturing system.

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