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A SOFTWARE CONCEPT FOR PROCESS CHAIN SIMULATION IN MICRO PRODUCTION

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ABSTRACT

Microstructure technology is one of the key technologies of the 21st century. With a higher level of miniaturization, complexity of components and production processes increases. Despite high process uncertainties, micro components require very small manufacturing tolerances. As micro production is characterized by short production times and comparatively long setting-up times, process chain planning becomes an important factor for production efficiency. This article introduces a concept for the simulation of production process chains, which covers fabrication and material flow planning, while addressing process uncertainties and software needs. The main section concentrates on the software concept μ-ProST (μ-Process-chain Simulation Tool), which maintains the workflow and optimizes process chain design, by mapping an already existing methodical model into the software concept. Finally, the article provides an evaluation of this work, by presenting a prototypic simulation of a micro manufacturing decision scenario for a process configuration.

KEYWORDS

micro production, process chain, software concept, logistic size effects, simulation tool

1. INTRODUCTION

Nowadays, many manufacturing areas benefit from extremely small and reliable products. A sector in which established applications are settled very well is the medical one. For instance, minimal invasive surgery causes a minimum of stress as possible to the patient and accelerates the healing process. An current research field and future application of micro production is micro fluid engineering, where miniaturized laboratories enable secure mixing processes for explosive fluids. Although the trend of miniaturization is increasing, there is a knowledge lack of micro production processes, caused by two main reasons. First of all, size effects (Vollertsen 2008) affect the knowledge transfer from macro to micro production. Such a size effect could be a change of the surface-to-volume ratio which occurs by downscaling the product volume. Secondly, micro manufacturing imposes special logistic constraints (see Chapter 2 for examples). Consequently, a better understanding of micro production processes is becoming increasingly important. Common tools to gain information about a physical system, such as a production process, are:

- Mathematical models,
- real-world experiments, and
- computational simulations.

A mathematical model is a clearly defined process description which approximates the behaviour of a complex process. Naturally, the quality of a mathematical model depends mainly on the quantity and quality of the underlying system observations, mostly given by experimental data. To predict unknown or future process behaviour the use of virtual experiments, i.e. computational simulations, can be of great importance. Imagine a scenario with the aim to predict the CO_2 amount of the atmosphere in the year 2050. Obviously, it is not acceptable to wait until the end of the experiment to get the wanted information. However, a simulation, based on given models and experiment data, might achieve the result with sufficient accuracy.

To satisfy industrial customer needs, product developers have to focus on cost effective micro product and production processes, aiming at a profitable and reliable middle and high volume production. However, a high level of miniaturization leads to a high degree of production process complexity. The size-effects result in high production process uncertainties. Additionally, micro production processes are characterized by a high number of interacting factors. Hence, slight parameter changes in early production steps may cause unpredictable parameter changes in later steps. To avoid high amounts of sub-standard goods, the process parameter configuration has to be conducted within reasonably small ranges of tolerance. Due to these influences, micro production requires comparatively long set-up times and high reconfiguration costs. With regard to production efficiency, process chain planning becomes an important factor for micro production. Process chains include all production steps that have an impact on the product quality, including parameters of material, tools, and associated product components. Based on the need for a better understanding, various scientific research has already be done on the micro production process topic (Vollertsen 2004, Piotrowska 2009, Hu 2009 etc.). Most publications focus on downscaling of the production process for single product components. Therefore, it is not sufficient to study single production processes, but the whole process chain must be taken into consideration. However, up to now a holistic concept for process chain planning in micro production is missing.

To face the scientific and conceptual challenge of process chain planning, this research presents the software concept µ-ProST (µ-Process-chain Simulation Tool), which combines a process chain model with simulation and experimentation. To motivate the need of such a software concept, this paper gives a short overview of the special constraints of micro production and arguments why the use of planning tools from macro production is not sufficient. Thereafter, a process chain model concept is introduced, based on the corresponding production process models. Afterwards, the process chain simulation concept allows the transfer from qualitative to quantitative technical cause-effect relationship information.

2 MICRO PRODUCTION

Intensified investigations on the physical aspects of micro production demand a clear definition of micro components. Vollertsen defines a part as a micro component, if and only if at least two of its geometrical dimensions are smaller than one millimeter (Vollertsen 2004). Micro production processes are employed to produce or handle such micro components. Commonly, the development of micro products and their production processes is motivated by the desire to scale down already existing macro products. In order to gain a downscaled product, all relevant length dimensions of the process parameters are reduced in a similar way, i.e. by a constant factor. Nevertheless, micro production stands for more than the mere physical act of manufacturing. Micro production includes assembling of micro components, micro tooling and handling of the components as well as production process planning and process parameter adjusting. On a micro scale there are several influences on production efficiency, which affect the use of conventional planning methods in macro production. For simplification, the subsequent paragraphs use a µ instead of micro, i.e. µ-component for micro component.

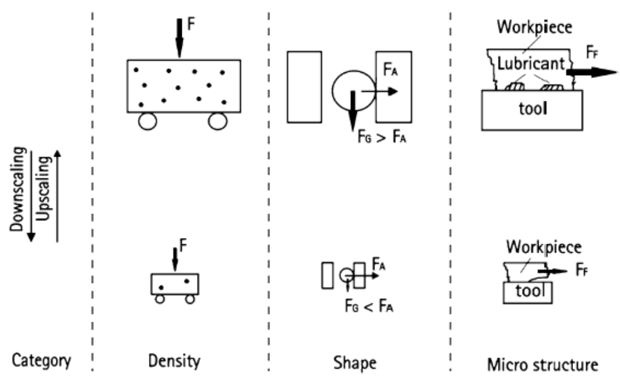

Fig.1 Schematic representation of the three main groups of size effects F force F_A adhension force F_f friction force F_G gravity (Vollertsen 2009)

2.1 SIZE EFFECTS

At first sight, the development of a µ-production process, under the assumption of a well known macro process, seems to be a simple task: If the process, including all process properties, is scaled down in a similar way, then the product will be as well. Although, this is theoretically true, the downscaling of all dimensions and forces relevant to the production process is not possible. For instance, it would have to include the downscaling of natural constants, such as the density of material, or the gravity force. The deviations of the process properties, which occur, the geometrical dimensions and thereby the product mass are scaled down, are called size effects.

To understand the origin of parameter deviations, two parameter types are distinguished: Parameters which do not change with the mass are called intensive variable*,* whether those which change with mass, called extensive variables*.* The size effects can be divided into three main categories: density, shape and microstructure (Vollertsen 2009). Shape effects occur due to the fact, that holding the shape constant during downscaling leads to a change in the relation of surface to volume. The shape effects are distinguished into surface-related ones and those which can be described as a sum of volume and surface related sub values, while the relative amount changes during scaling. The last category, the microstructure effects combine all effects that occur because the simultaneous downscaling of all structural values is physically or practically not possible. An overview of the size effect categories is given in Figure 1. With regard to a manufacturing scenario, the value of size effects can be beneficial as well as neutral or detrimental for the whole production process.

2.2 LOGISTICS IN MICRO SCALE

Similarly to the physical specifics of micro manufacturing, the properties and logistics of production processes in micro production differ from the macro production ones.

By scaling the geometrical dimensions, process parameters, such as the product dimensions, weight, hardness, and sensitivity are affected in a direct way. Further, the strength of environmental influences, like temperature, dust, contamination, humidity or electrostatic is growing. Hence it is neither possible to describe micro production logistics by simply downscaling the processes from macro to micro scale and investigations on the logistic behavior of micro processes are necessary.

2.2.1 Logistic Aspects in Micro Production

In particular, several parameters relevant to the production efficiency, change as consequence of the size effects and thus enforce changes in the process properties. For instance, due to the increased surface-to-volume ratio of micro parts, their gravitational force is lower than the adhesion forces. Hence the handling and the assembly of μ-components differs from macro production. Thus the development of handling techniques is a great challenge in μ-manufacturing. One possibility to avoid handling conflicts is to produce components in a larger composite and strive for a separation as late as possible. This way, they can be handled with standard conveyer machinery like macro parts. Otherwise, intentional use of micro components gives new ideas on process realizations becoming possible only due to the size effects. For example contactless transportation systems using air stream take advantage of the relative small gravitational forces (Moesner 2004). Developing micro specific processes enables effective production and is a great challenge of micro technology research.

A fundamental aspect of the efficiency of μ-production processes is a constantly high product quality. In micro production, precise manufacturing is decisive for product quality. Thus, geometrical structure deviations below one micrometer are a common goal setting. To ensure the high quality requirements, quality tests have to be made. Up to now, standardized methods and instruments for automated quality inspections are missing. The limited resolution of optical instruments results in measurement uncertainties. Thus, there is a knowledge lack about the behavior of μ-production processes and their parameter relationships. These arguments, combined with the fact that μ-production processes are highly sensitive and component post processing is not feasible, lead to the conclusion, that manufacturing constantly high quality is a main task, for micro production and requires very small manufacturing tolerances.

In addition to these technology based consequences, production and logistics related effects like the possible use of smaller machines lead to new potentials in μ-production planning. As micro production is characterized by short production times, a micro factory has to be able to handle short and unpredictable product orders. Thus a flexible job planning and a daily process adaption to new orders are essential. High investment needs and fixed cost, which can be found in the large ratio of machine costs, are another relevant factor to efficiency.

Large product ranges and small series production cause frequent setup procedures. Hence, to avoid investment risks and idle machines, an efficient planning and forecast of resource and engine supply the lack of stable processes and standardized interfaces as well as suitable handling and measurement methods in the micro scale, production process planning has to be integrated at an early state of the product development process. (Scholz-Reiter et.al 2010) Therefore, the μ-ProST software concept involves an integrated μ-process chain planning tool including handling operations, assembly, quality tests and investment planning. Several research groups are facing the challenges given by single micro manufacturing problems.

2.2.2 Planning of Micro Process Chains

Due to high accuracy and a strong dependency between quality, handling and manufacturing in μ-production processes, the approach of parallel planning of these three fields has been made (Scholz-Reiter et.al 2010). The proposed concept of an integrated μ-process chain provides a framework for the generation of a tool for production planning with special respect to characteristics found in micro production.

A manufacturing process chain describes the chronological and logical order of all operations necessary to produce the micro component or subassembly. Due to the complexity of planning constraints, assembly and test operations have to be taken into account at an early state of the production planning in order to avoid later cost and time efficient adjustments. This means that production technology, test and handling techniques are simultaneously developed. Thus, possible adaptation problems between production technology and handling operations, including discrepancies in handling time, can be detected early and bottlenecks can be found. The aim of the integrated micro process chain concept is to provide a basis for production program planning. The coordination of planning processes demands standardized descriptions of processes and their interfaces. Challenges rest on their systematic preparation and presentation.

In summary, production process chain planning has to be integrated in the product development process. To accelerate the setting up times a software support is necessary.

3 SOFTWARE CONCEPT

The special constraints in micro production entail the application needs of a micro planning tool. To meet these consequences, the first section of this chapter presents a component list of the main software a planning tool kit should include. In the second section the μ-ProST software concept is presented.

3.1 SOFTWARE REQUIREMENTS

This section presents the software component of software a planning tool kit.

Fig.2 The μ-ProST GUI, including the adjusted DESMO-J simulation tool

3.1.1 User Interface

Due to flexibility of processes and machines, the proposed software has to include a user interface. The user interface allows updating and addition of new data, as well as creation of production or investment scenarios and evaluation methods. Of course the user interface should be clearly structured and support uncomplicated operation. A help function, demonstrational models and simulations are useful supplementations.

3.1.2 Database

The software kit has to organise and store different types of data (product, tool, machine, customer etc.). Therefore, a database is one of the basic software parts. As high volume production of μ-components is an actual research field, effective data storage is potential to provide the groundwork for precise predictions. Moreover, the database forms the substructure needed to forecast costumers behaviour and to get valuable statistical data of micro technological properties.

3.1.3 Process Chain Model

As interaction of the production steps among the production chain is important to achieve sophisticated products, the internal representation of a process chain is a decisive factor. Thus, changes in the process chain system have to be part of the model concept. Micro production processes are characterized by a high number of interacting factors.

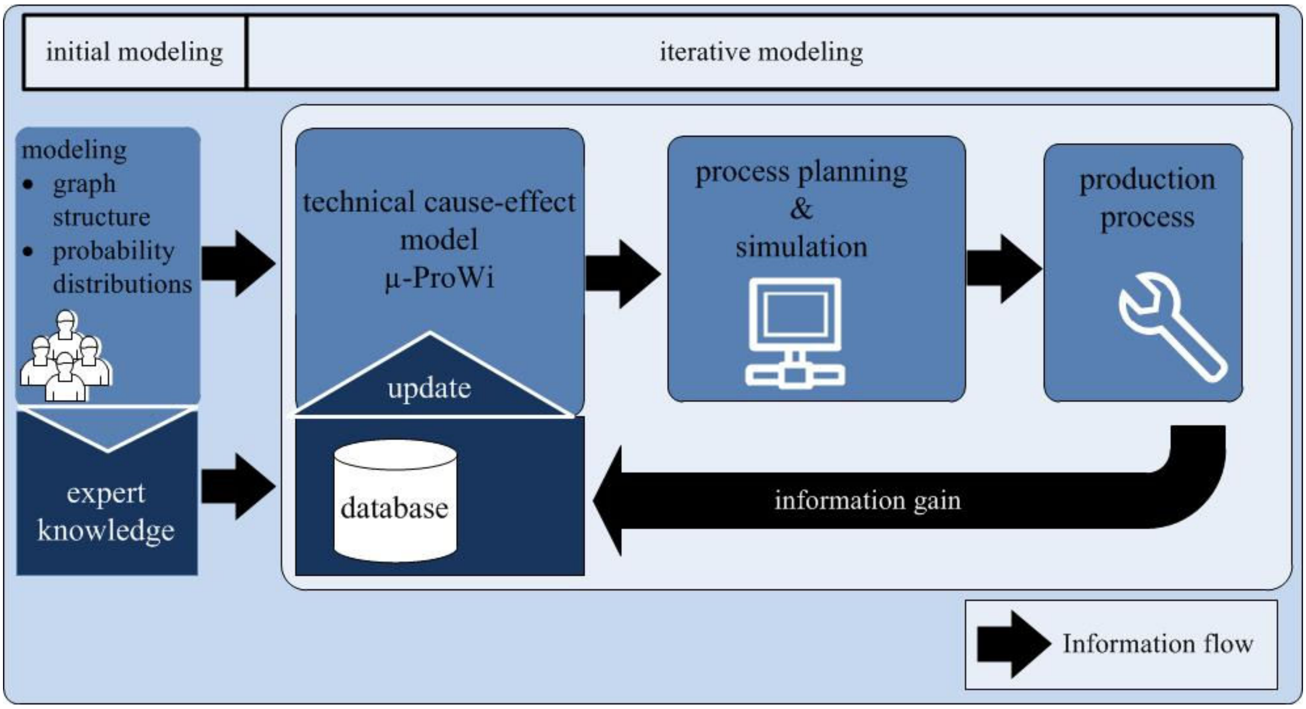

Fig.3 Information flow during the development of the technical cause-effect model

Hence, slight parameter changes in early production steps may cause unpredictable parameter changes in later steps. To avoid a high amount of sub-standard goods, the process parameter configuration has to be conducted within reasonably small ranges of tolerance. As a result, error propagation becomes an essential instrument for the control of product quality. Therefore, a sufficient detailed description of the cause-effect relationships should be part of the process chain model, to detect critical parameter constellations in early configuration steps and avoid high configuration costs.

3.1.4 Micro Process Models

The µ-ProST software tool does not compensate the missing development of process models. Although the software is able to detect and handle a certain amount of model flaws, precise process modeling is a decisive preliminary work. Therefore, we assume given physical or mathematical model descriptions for all production steps. Every single model derives the process step outcome from the process step input, taking into account all parameters relevant to process description and local technological cause-effect relationships.

Aiming at optimal use of all existing process information, the software should be able to handle and store different model types. The most common models are differential equations systems (for further information a detailed overview of mathematical models see Imboden 2008)

3.1.5 Simulation Tool

As the software acts as a planning tool, the most important user application is the simulation tool. In order to guaranty short set-up times and to satisfy the flexible needs of a micro production company, a fast simulation method is indispensable. Additionally, dealing with a limited amount of knowledge gaps or process uncertainties may be necessary.

3.1.6 Additional Interfaces

The high impact of parameter interactions in process chains demands a fundamental understanding of the used technologies, the process properties and the process interactions. Additional interfaces, such as model solvers, accelerate the process chain simulation by outsourcing complex derivations to suitable software resolutions.
Finally, an interface for realtime data recording completes the software tool kit.

3.2 THE µ-PROST SOFTWARE CONCEPT

The software concept for the **µ-Pro**cess **C**hain **B**ased **S**imulation **T**ool (µ-ProST) is a model based planning system. Due to current updates of the technology state the µ-ProST software can serve as a central planning and documentation tool in a micro factory. As a preliminary work before the start of the simulation, the initial process models must be developed. An overview of the development steps is given in Fig 3.

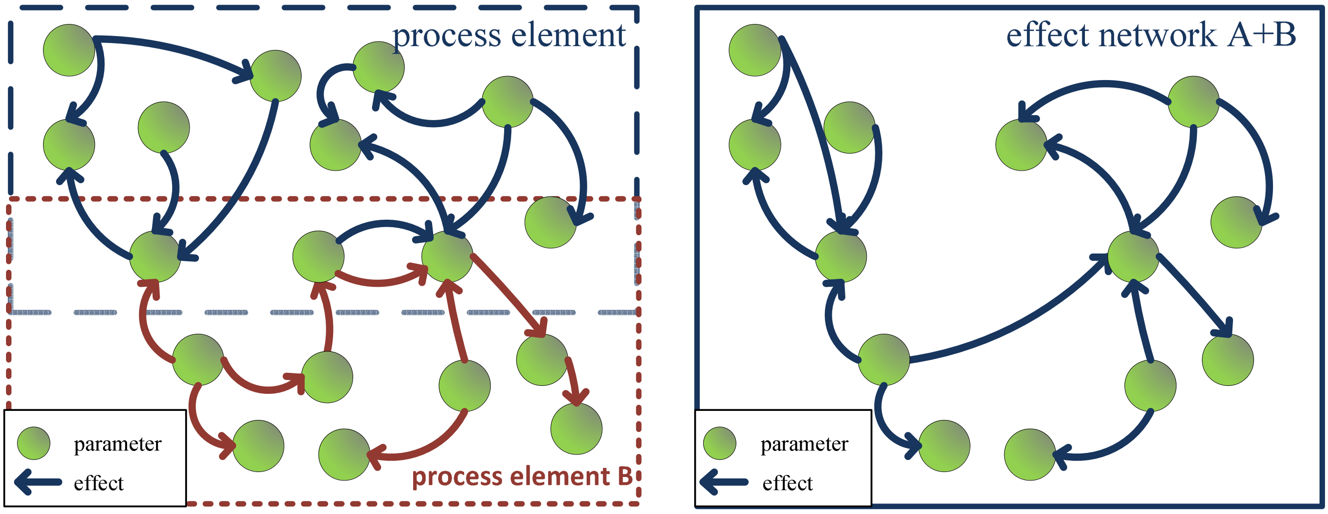

Fig.4 cause-effect relationships of process parameters (a) effect-network for the interface of two process steps (b) reduced graph of the process chain

To satisfy the high number of different data types, object oriented programming is chosen. To achieve a simple software structure and fast computing, the decision was made to use a Java based software development.

As the common service functions (GUI (see Figure 2), database, graphical evaluations, job scheduling etc.) do not differ much from a software realization for macro production, the next section highlights only two software components which are adapted for the special constraint of micro production. These are the software representation of the process chain model and the adapted use of a Java based Simulation tool, DESMO-J.

3.2.1 Process Chain Model Concept

For the simulation of a µ-production process the mathematical and physical models, representing steps of the process chain, have to be implemented and linked. We use the technical-cause-effect relationship based process chain model µ-ProWi (Scholz-Reiter 2009). The holistic model approach is part of the CRC 747 research work. The µ-ProWi model approach expresses the qualitative technical-cause-relationships in terms of directed, acyclic graphs, called effect-networks. The nodes of the network represent process variables. Process variables may be observable quantities, latent variables and also unknown parameters. The edges represent technical-cause-effect dependencies between the process variables. A successful implementation of the *µ-ProWi* model will able to forecast general interactions of process parameters and thus to identify significant control factors. Hence, effect-networks allow the representation of technical-cause-effect relationship information.

To quantify the cause-effect relationships, we assume an extended modeling concept. Based on the µ-ProWi model approach, the cause-effect relationship graph is extended to a Bayesian network with continuous variables (Jensen 2001). Due to the continuous parameter representation, different parameter states can be distinguished and the impact of parameter changes can be evaluated. The technical-cause-effect relationship can be represented by probability distributions. The construction and specification of the Bayesian network is divided in two main steps. Firstly, the graph structure is defined. Secondly, the probability function has to be modeled. The graph structure is given by the qualitative µ-ProWi model, given by the scenario input of the user. The computation of the probabilities is usually founded by experimental datasets. If a huge data base is available, the software should use it. If not, and that is the normal case in micro production, the model must be approximated by the given knowledge as good as possible (using the given process models and simulation methods to create a simulation based database). A combined model approximation, involving uncertainty representations, such as fuzzy logics, may be a good initial solution.

3.2.2 Process Chain Simulation

The existing information structure suggests an iterative simulation procedure, based on the material flow among the process chain. Hence, the process steps can be implemented and calculated separately.

As a simulation framework we choose DESMO-J (**D**iscrete-**E**vent **S**imulation and **Mo**deling - with **J**ava), developed by the university of Hamburg (Lechler 1999). Several aspects make the DESMO-J framework perfect for µ-process chain simulations. DESMO-J supports an object oriented model representation and provides a complete separation of model and experiment. As an open source project, DESMO-J is adaptable to our special

conditions. Furthermore, a wide range of useful method implementations relevant for process oriented modeling, such as stochastic distributions and statistical data collectors, can be adopted. Moreover DESMO-J supports the synchronisation of simulation processes, which are acting concurrently or allow a process interruption.
Finally, DESMO-J supports both, process-oriented and event-oriented model style, also known as process-interaction approach or event-scheduling approach, respectively.

The μ-ProST simulation approach extends the process oriented simulation methods by an additionally black box model. The production process chain is interpreted as a dynamic system x(t) generating an output y(t) dependent on an input u(t), where x, y and u are continuous vectors and t is the simulation time. Hence, the process steps can be implemented and calculated separately. The input u(t) consists of all measurable production relevant factors, including machine parameters. The output y(t) represents the manufactured micro product, including information about the logistic effort and product quality. The simulation of the system behavior is divided into different production steps and their models, based on the material flow. Every single production step itself is represented as a dynamic system (black box model). The behavior of the production step system may iteratively be defined by a smaller intern process chain or by a given process model. The system interfaces are fixed by the input and output of the process steps. Hence, the simulation of parameter change propagation is possible. A high repeating simulation rate with changing parameter constellations allows the simulation of whole screening plans. Running the simulation with given process step models leads to a data base which enables the quantitative modeling of cause-effect networks. If the structure of the networks is not limited, this may induce networks of extremely high order and complexity. (Figure 4a). The reduction to a minimalistic acyclic graph is a necessary task (Figure 4b). Suitable methods for the graph reduction and the training of the conditional probabilities (i.e. the Expection-Maximization-method, Jensen2001) must be chosen.

3.2.3 Interaction of Process Chain Simulation and the Technical-Cause-Effect Model

As quality is strongly dependent on the process chain simulation and the technical-cause-effect model we go in detail with the interaction. On the one hand, the gained data information of the process chain simulation and the parameter dependencies in between allows a better understanding of the technical-cause-effect relationships and thus a correction of the process chain model. On the other hand, a successful simulation only is possible if the underlying process chain model, consisting of the process step models, has been well defined. Thus a solid process modeling and experimentation stays a primary task. No software tool can to replace the research work and technical expertise. Nevertheless, if the simulation leads to a better model and a better model leads to a better simulation, a repeating of the information gain cycle may be a possibility. Research to study such an iterative information gain has not been done yet. Another interesting investigation field is the error behavior depending on the process chain model quality. Maybe starting criterias assuring restricted error ranges in the simulation can be found.

3.3. EVALUATION

In Order to demonstrate the principle software use, a prototypical production scenario is implemented. We assume a micro factory where a new production process should be installed. The new μ-product **c** requires the assembly of two product components. Product component **a** must be served by engine type A, component **b** by engine type B. In a second production step components **a** and **b** are assembled by engine C. The assembly engine C is a fixed process element, which cannot be changed. The quality of product **c** depends on the incoming product components qualities and an unknown influence of engine C. In contrast to the assembly engine, the production properties of engines A and B are known. For both, production step A and production step B, two engines (A1,A2,B1,B2) are available. The engines differ in production costs and manufacturing quality ranges. The influence of the engines on product component quality is given by a statistical distribution. The quality is defined by a number between zero (defect) and one (best quality). The more expensive engines produce a higher product quality. The Engines parameters are listed in Table 1.

Table 1: Engine characteristics

Engine	Quality Distribution	Costs/day
A_1	U(0,8,1)	500
A_2	U(0,75,0,95)	200
B_1	N(0,9,0,1)	300
B_2	N(0,6,0,25)	200

Based on the engine characteristics, a decision plan shall be made. Thus, in case of a new product order, a fast decision, which engine combination fits optimal to the process chain and delivers a maximum profit, is supported. Due to the costumers requirements, only products fulfilling a certain threshold can be sold. Hence the profit depends on the customer demands and the products actual market price.

To enable a simple product quality forecast, the behavior of engine C must be approximated. Due to the knowledge from macro production, we assume that the product quality of product **c** depends strictly on the quality of the subcomponents **a** and **b**. Thus, the arithmetic average of the subcomponents' quality is taken. The prototypic forecast simulates the production of twenty samples and derives the product components and final product quality. The qualities for the engine scenario (A1 B1) are plotted in Figure 5.

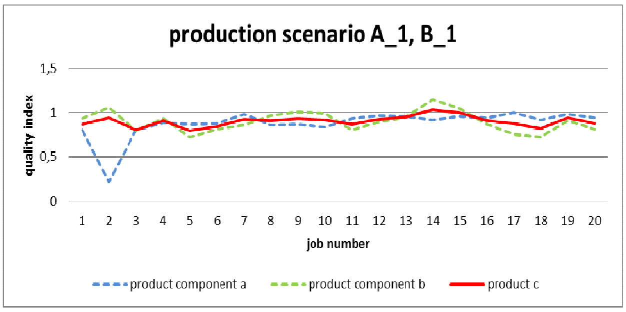

Fig.5 product quality of an prototypic simulation scenario

To compare the engine scenarios the same simulation was applied for all combinatorial possiblities. The resulting qualities of product **c** are plotted in Figure 6.

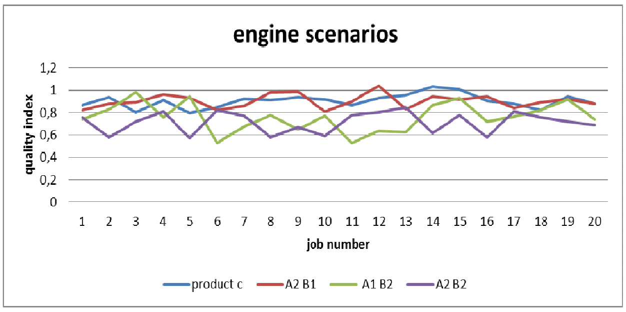

Fig.6 product quality comparison of the four of prototypic simulation scenarios

As expected the engine scenarios including the more expensive engines generate a higher product quality. In order to compare the value of the engine scenarios the production profit with respect to manufacturing costs, must be plotted against the quality threshold and product price. We did a prototypic profit plot for the first two scenarios A1 B1 and A2 B1. The results are shown in Figure 7. high regions represent the threshold price combinations which allow a profitable manufacturing.

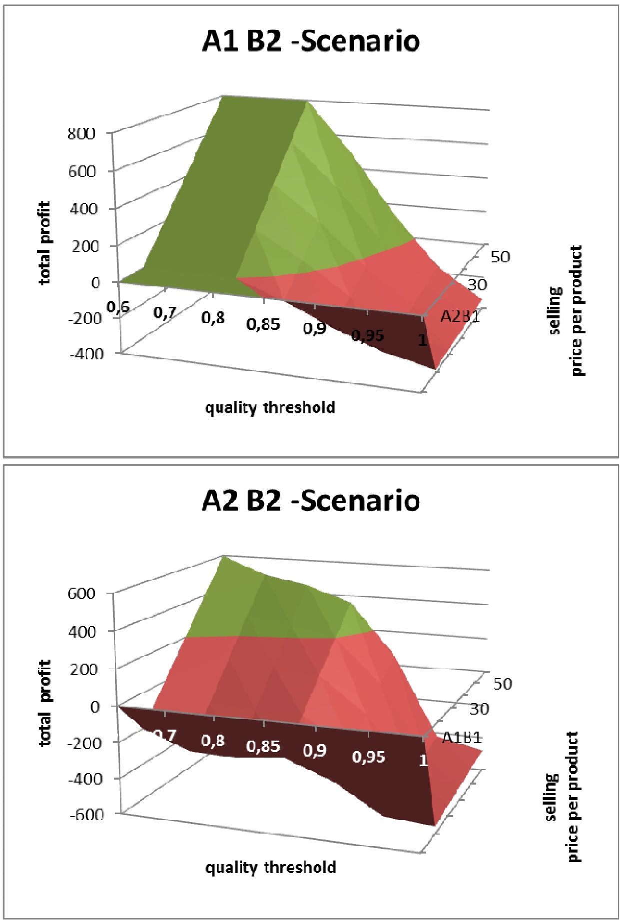

Fig.7 profit matrix of the engine scenarios

Based on these data, a suitable engine combination can be chosen rapidly, when a new job order arrives. Obviously it is possible that during the set-up of the process chain the behavior of engine C does not consist with the supposed one. For instance, product quality may be nearly independent from one or more product components. Thus, the experimental data of the set up process can be taken to update the missing knowledge and to gain a better model of the assembly process step.

5. CONCLUSIONS

With respect to the complexity of micro components and production processes, a planning tool is essential for effective high volume manufacturing of micro components. Aiming such a planning support, this paper first presented an overview of the restrictions on micro production engineering. We figured out, that beside the physical aspect of a production process, also the logistic process parameters suffer size-effect changes while downscaling the product dimensions. Based on the special logistic constraints of micro production, this article derived the need of a planning software. The introduced μ-ProST software concept provides a solution for the simulation of complex process interactions in micro production and is able to detect quality relevant process parameters in early configuration steps. Finally, a prototypic application on a micro manufacturing decision scenario for a process configuration problem was presented. First, the software generates an initial process model, based on given fragmentary process data and additional interaction assumptions. Second, the best possible process configuration is calculated. With the beginning of the production process new data becomes available. Thus the process model can be corrected. In the given scenario, the resulting information gain about the cause effect relationship between the engines allows the manufacturer to change the process configuration and to raise the overall production profit. In summary, a planning tool regarding the special constraints of micro production is a worthy tool, both in research, to gain information about unknown parameter and size effect interactions, as well as in the industrial sector. Nevertheless to proof the feasibility of planning problems with a high degree of complexity is a main future task.

6. ACKNOWLEDGMENTS

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