Managerial manufacturing technology : specified for the influence of manufacturing technique on managerial aspects of process planning for small batch manufacturing

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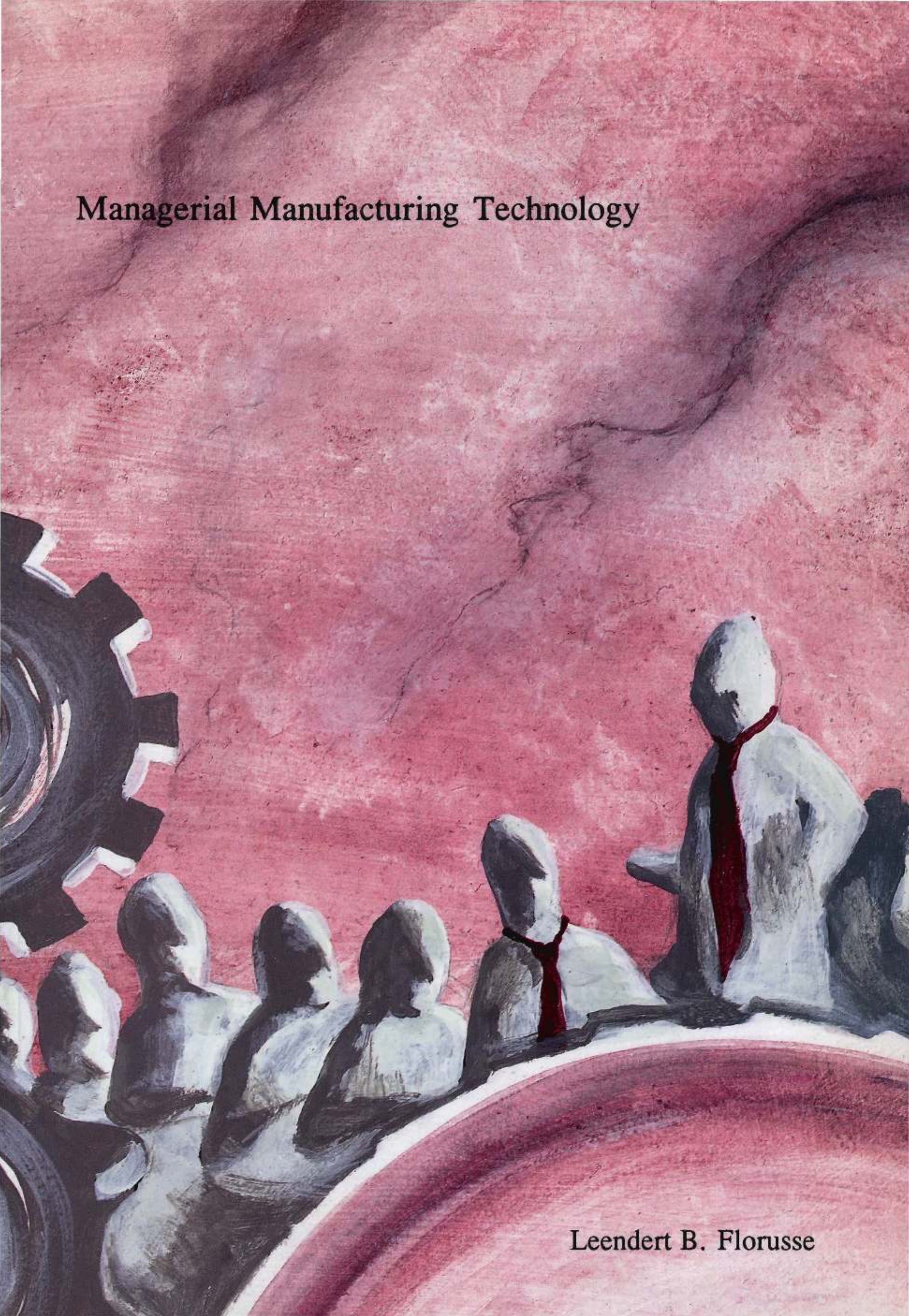
Managerial Manufacturing Technology



Leendert B. Florusse

Managerial Manufacturing Technology

specified for the influence of manufacturing technique on managerial aspects of process planning for small batch manufacturing

PROEFSCHRIFT

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een commissie aangewezen door het College van
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Leendert Berend Florusse

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prof. dr J.Wijngaard
en
prof. dr ir G.Gaalman
en door de copromotor
dr ir A. van de Ven

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VOORWOORD

Eindhoven, december 1992

Geen proefschrift komt tot stand zonder de medewerking van (vele) personen. Degenen die meewerkten aan dit proefschrift wil ik in dit voorwoord graag bedanken.

Toon van de Ven, co-promotor, was degene die mij op het idee bracht om te gaan promoveren en ook bij het hele project betrokken bleef. Jacob Wijngaard trok het onderzoek inhoudelijk vlot op het moment dat bij de (voormalige) vakgroep TPS geen begeleidingscapaciteit meer voorhanden was. Hij was uiteindelijk bereid als eerste promotor op te treden. Door de begeleiding van Toon en Jacob bleef het promoveren boeiend en, inhoudelijk en persoonlijk, een belangrijke ervaring. Gerard Gaalman en Fred van Houten dank ik voor hun bereidheid in de kleine commissie zitting te nemen en voor hun constructieve commentaar op conceptversies van dit proefschrift.

De heer D. Slager droeg enorm bij aan het onderzoek doordat hij het praktijkonderzoek bij Fokker Aircraft initieerde en enthousiast ondersteunde. Hopelijk maakt dit proefschrift van zijn inspanningen een 'winstgevend' project. Ir C. van Luttervelt (TU Delft, werktuigbouwkunde) gaf zeer instructief commentaar op diverse stukken. Prof. ir J. Kals (TU Eindhoven, werktuigbouwkunde) was ook enige tijd betrokken bij het onderzoek. Hoewel, naar zijn idee, de kloof tussen bedrijfskunde en techniek niet nauwer gemaakt kon worden is zijn inbreng toch zeer zinvol geweest.

Natuurlijk gaat mijn dank evenzeer uit naar de medewerkers van de bedrijven die hun medewerking gaven aan het veldexperiment. Met name moeten worden genoemd: Rob van Dorp (Fokker Drechtsteden, Papendrecht), Gert-jan Streefland (DAF Trucks, Eindhoven), Geert van de Kerkhof, Hans van der Heijden & Noud Martens (Rueti te Strake, Deurne), Mario Leijdekkers & Frank Leijten (VDL-TIM Hapert, Hapert), Michel Venema & Jan Muijen (BUVO, Helmond), dhr. van de Venne (Nefotaf, Weert), Marcel Crooymans & Sjaak Schattefor (RENA, Maasbree).

Op uitnodiging van professor Clausing van het Massachusetts Institute of Technology kon ik in de zomer van 1992 drie maanden aan het Laboratory for Manufacturing and Productivity werkzaam zijn. Mijn dank gaat uit naar professor Clausing voor het leerzame en vruchtbare verblijf in Cambridge.

Verder wil ik de collega's van de vakgroep BM, met name Jacques Theeuwes, noemen. Hen dank ik voor de bereidheid mij in de vakgroep op te nemen toen verder werken in de vakgroep TPS onmogelijk was geworden. De goede sfeer in de vakgroep was zeer stimulerend. Hetzelfde geldt voor de collega promovendi in Groningen, Twente en Eindhoven met name de deelnemers aan de eerste NOBO methodologiecursus. Met name het gezamenlijk publiceren met collega Marc Wouters was zeer stimulerend. Deze 'onderzoeksschool' heeft in belangrijke mate bijgedragen aan het slagen van mijn promotie.

Mijn vrouw Els bedank ik voor de schitterende omslag.

SAMENVATTING

Het doel van het promotieonderzoek, waarover dit proefschrift rapporteert, was te komen tot een bedrijfskundige beschrijving van fabricagetechniek. Wat een dergelijke wijze van beschrijven betekent wordt beschreven in een systematische analyse van het onderzoeksgebied van Technische Bedrijfskunde. Daaruit wordt geconcludeerd dat de Technische Bedrijfskunde beschouwt doelgerichte mens/middelen systemen die fabricage- of ontwerp/ontwikkelactiviteiten in bedrijven integreren. Meer specifiek beschouwt de Technische Bedrijfskunde dan de taken in, de organisatie, de informatievoorziening en besturing van deze systemen. In het licht van het onderzoeksdoel betekent dit dat de relatie tussen technische fabricagemiddelen en die aspecten moet worden onderzocht.

Korte productintroductietijd is een steeds belangrijker factor in de concurrentiestrijd in de industrie. Bij discrete producten wordt een belangrijk deel van de productintroductietijd en -kosten ingenomen door de werkvoorbereiding. Voor producten die worden gemaakt in kleine productievolumes en -series is het belang van deze activiteiten relatief nog eens extra groot. Werkvoorbereiding voor discrete productie in kleine productievolumes werd daarom gekozen als onderwerp voor nadere studie. Dit betekent dat de bedrijfskundige aspecten van werkvoorbereiding moeten worden verbonden met kenmerken van fabricageprocessen en -middelen.

Uit een literatuurstudie kan worden geconcludeerd dat structuur en capaciteit (kwalitatief en kwantitatief) voor een organisatie moeten worden afgestemd op de onzekerheid in de taken van de leden van de organisatie. Die onzekerheid kan worden gedefinieerd als het verschil tussen de voor de taak beschikbare informatie en de voor die taak benodigde informatie. Op grond van een modelmatige beschouwing werd de hypothese geformuleerd dat de taakonzekerheid in werkvoorbereiding stijgt naarmate meer variabelen van een bewerkingsproces onderling afhankelijk zijn en naarmate de meetschaal waarop werkstukkenmerken en procesvariabelen kunnen worden gemeten van een lagere orde is. In een veldexperiment werd de hypothese bevestigd. Op die manier zijn

kenmerken van de techniek in de fabricage verbonden met bedrijfskundige variabelen.
Via een theoretische studie kon de relatie tussen machinekenmerken en taakonzekerheid in de werkvoorbereiding worden onderzocht. De technische selectie van een machine draagt nauwelijks bij tot die onzekerheid. De keuze van de machine op grond van economische en logistieke criteria draagt echter sterk bij tot de taakonzekerheid. Dit is te wijten aan de onbekende prestatie van de machine en aan de interactie tussen het toewijzen van een werkstuk aan een machine en de toewijzingsmogelijkheden voor andere werkstukken. Voor het logistieke criterium is een belangrijke beïnvloedende variabele nog het beheersingssysteem dat in de fabricage wordt gehanteerd. Dit bepaalt de mate waarin reallocatie van werkstukken over machines mogelijk is.

De resultaten van dit proefschrift kunnen worden gezien als een basis voor een systeem voor ontwerp en beheersing van een werkvoorbereiding(safdeling) in een fabricage bedrijf in de kleinseriefabricage en geven een beeld van de mogelijkheden van technologische kennisopbouw als functie van de technische middelen in de fabricage.

SUMMARY

The aim of this thesis is to observe manufacturing technique from an Industrial Engineering and Management Science (IE & MS) viewpoint. It is not obvious, however, what this means. From a systematic analysis of this research problem the following conclusion is drawn. IE & MS observes the integration with external demand of manufacturing and design/development activities as goal-oriented, integrated, man/means systems. In doing so it studies the appropriate capacities, organization and control for these activities. Given the research objective, this thesis should investigate the relation between the technical means in manufacturing and the mentioned aspects of the integrating activities.

Short product introduction time is an increasingly important source of competitive advantage in industry. For discrete products, that are produced on a given set of resources in small total quantities, an important part of the product introduction time is spent on process planning activities (i.e. the translation of product data into manufacturing instructions). Therefore, the integration of process planning was chosen as the subject for further study in this thesis.

It is found that, in the literature, technology on the one hand and on the other hand organization structure and capacity demand (qualitative and quantitative) are linked through the concept of task uncertainty. Task uncertainty can be defined as the difference between the information available for a task and the information needed for a task.

Based on a general model of manufacturing processes and on a general description of parts, a research hypothesis is formulated. The hypothesis says that the more manufacturing process variables are interdependent and the lower the measurement scale of part characteristics and manufacturing process variables, the higher the task uncertainty in process planning. The uncertainty is expressed in a.o. the skill-level and the time needed for the different process planning tasks. A field experiment confirmed the hypothesis. In that way, a link from technique to managerial aspects of process planning has been made.

Also, in a theoretical study, the influence of manufacturing resources availability on process planning uncertainty is analyzed. It can be concluded that the technical machine selection does not add much to process planning uncertainty. The economic and the logistic criterion in the machine choice, however, add to the uncertainty in process planning. For the economic criterion this is mainly due to the unknown performance of a machine, the unknown investments for fixtures etc. and the cost effects of reallocating other jobs. For the logistic criterion the uncertainty is mainly due to the interaction (in capacity utilization) with other jobs. However, this effect depends on the control philosophy in production. OPT and KANBAN only seem to allow for feed forward balancing/optimization of capacity usage.

The results of this thesis can be a basis for a tool for planning and control of process planning activities and thus for improvement of the product development process. It also sheds some light on the possibilities for process planning automation and the indirect effects of manufacturing technique.

INTRODUCTION

Short product introduction time is a major competitive weapon in industrial competition today. Especially for companies that produce discrete products in small lot sizes and total series this means that the control of the product design/development process is extremely important.
In this thesis it is shown that process planning is a major contributor to product development time and -costs in small batch manufacturing (e.g. Hebbeler, 1989). The time and costs for process planning strongly depend on the manufacturing processes and resources chosen for making a part. Technological developments result in an increasing number of alternative processes and resources (e.g. Van Luttervelt, 1989). Therefore, insight into the relation between, on the one hand, characteristics of manufacturing processes and -resources and, on the other hand, costs and time for process planning would be an important contribution to the Industrial Engineering and Management Science (IE & MS) field. Earlier research investigated this relation only in general terms (Goswami (1973), Baberg (1980)) or only for specific processes (Almenraeder, 1983). In this thesis hypotheses on such relations for manufacturing processes are derived from the literature (Galbraith (1973), Perrow (1967)) and are tested in a field experiment. For manufacturing resources this is done through desk research and deduction.

First, in chapter 1, a dissertation on the research area of IE and MS is given. In chapter 2 the development of the competitive criteria in industry are derived from the literature and process planning is chosen for further study. In chapter 3 some new concepts for the IE and MS observation of manufacturing technique are presented. In chapter 4 a hypothesis on the relation between characteristics of manufacturing process and IE & MS aspects of process planning is formulated. The relation is constructed through the concept of task uncertainty. The hypothesis says that the more manufacturing process variables are interdependent, and the lower the measurement scale of part characteristics and manufacturing process variables, the higher the task uncertainty in process planning. The uncertainty is expressed in a.o. the skill-level and the time needed for the different process planning activities. Chapter 5 reports on the field experiment that was carried out to test the hypothesis. The experiment confirms the hypothesis. Chapter 6 treats the machine choice in process planning. It can be concluded that the technical machine selection does not add much to process planning uncertainty. The economic and the logistic criterion in the machine choice add much to the uncertainty in process planning. Finally, chapter 7 gives some conclusions based on the research presented.

CHAPTER 1

'Industrial Engineering and Management Science': a dissertation on the research area of the discipline

If one wants to incorporate the subject-matter of another research discipline in the theories of one's own research discipline, the question where to lay the border between the research areas of the different research disciplines comes up. The objective of this thesis is to incorporate production technique[1], the subject-matter of Mechanical Engineering, into the Industrial Engineering and Management Science[2] theory. In other words: if one looks at production technique from an Industrial Engineering and Management Science point of view, what then makes this point of view different from the point of view of other disciplines? This is the question that is tried to be answered in this chapter.
The answering of this question can be seen as a 'vague' problem, i.e. a problem to which there is no such thing as a 'right' or unique, optimal answer. A structuring of the problem situation is needed, more than an optimal solution. For this reason, the methodology advocated by Checkland (1981) was chosen for tackling the problem of delineating the Industrial Engineering and Management Science research area.
In section 1 a sketch of the problem situation is given. Then a definition of the relevant system, the production company, is formulated. This definition is worked out in a conceptual model (section 2 & 3). In section 4, based on this conceptual model, the research area of Industrial Engineering and Management Science (IE & MS) is described. The research areas of some other disciplines

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[1] The term 'technique' is used here instead of the popular term 'technology'. This is done in order to stress that hardware and physical processes are meant here rather than knowledge of hardware and processes. Further definitions of the term technique will be given in this chapter.

[2] 'Industrial Engineering and Management Science' is used here as a translation of the Dutch term 'Technische Bedrijfskunde'. The correctness of this translation is disputable. Since this chapter is a dissertation on the research field of the discipline 'Technische Bedrijfskunde' the readers who are not familiar with this academic discipline can derive their own translation from the contents of this chapter.

in Management Sciences and of Mechanical Engineering are also positioned in this conceptual model. This leads to an answer to the question what is specific to the IE & MS observation of manufacturing technique. Finally, section 5 concludes on the contents of the IE & MS research area. Thus, a first delineation of the subject-matter of this thesis is given.

1. A sketch of the problem situation and a first definition

If one looks at production technique from an Industrial Engineering and Management Science point of view, what then makes this point of view different from the point of view of other disciplines? As said, this is the question that is tried to be answered in this chapter. The answering of this question can be seen as a problem to which there is no unique, optimal answer. Checkland's methodology (Checkland, 1981) is a methodology for the analysis and structuration of problems for which there is no unique optimal answer and in which different views of reality play an important role. By structuring (modelling) the problem situation and by comparing models of the relevant systems in the problem situation with reality, the existing problem can be analyzed and solved. For this methodology, the relevant systems in the problem situation should be Human Activity Systems (HAS). HAS's are defined as (Wilson, 1990: 25): 'systems of human beings undertaking purposeful activity' and consist of an aspect system of activities (relations are logical dependencies, elements are activities) and a social aspectsystem (relationships are interpersonal, elements are people).

The methodology starts with a sketch of the problem situation. This means that the situation in which the problem evolved, rather than the problem itself, is worked out. For this, some basic facts and a sketch of what is problematic in this situation should be given. Essential in this phase is the explication of the 'Weltanschauung' (W) that prevails in the problem situation. Weltanschauung means the idea of the world, the notion of what is important, that (unconsciously) plays a role in the observation of this problem situation. In his book 'Systems Thinking Systems Practice', Checkland says that the sketching of the problem situation should be done by (Checkland, 1981: 163): 'recording elements of slow-to-change structure within the situation and elements of continuously changing process, and forming a view of how structure and process relate to each other within the situation being investigated'. Wilson (1990) suggests to start with a simple picture of the problem situation and to develop root definitions of the relevant systems in the problem situation, based upon that picture. This approach is chosen here. A simple picture of the problem situation under regard is shown in figure 1.

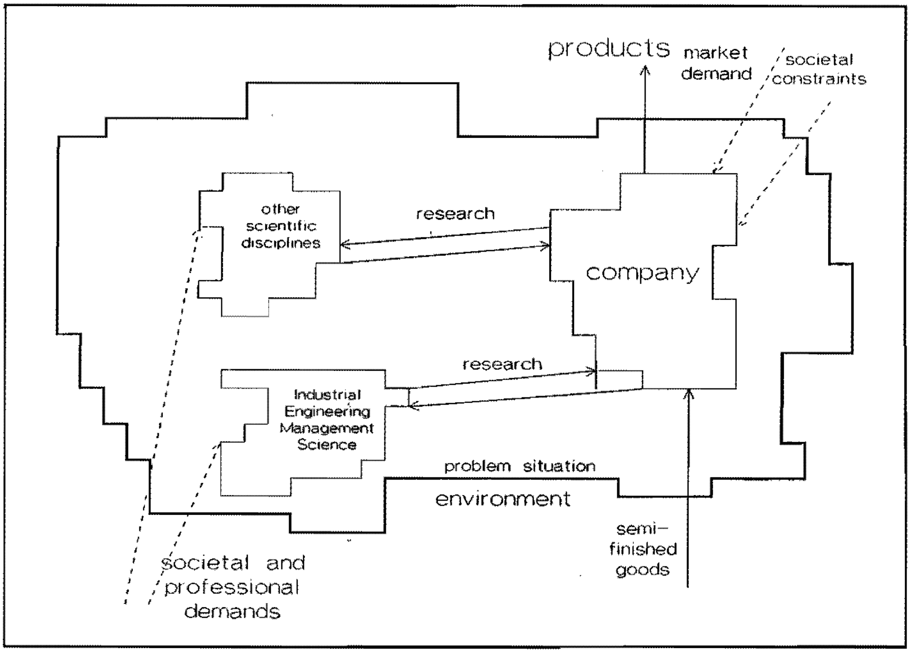

Figure 1. A sketch of the problem situation.

The problem situation here consists of several scientific disciplines all investigating (parts of) a company. Companies that apply the production techniques chosen as a subject for this thesis, transform semi-finished goods (or, more generally: materials) into products according to a certain market-demand. This transformation takes place within certain constraints which are formulated by society. The research disciplines also have to satisfy societal demands: e.g. effectiveness/efficiency criteria for research work formulated by governmental bodies. One of the consequences of these criteria is that the mutual research areas should be coordinated. Lack of coordination could lead to inefficiency: identical research is done twice or potential synergy is not used.

So, in Checkland's terms, the relevant structural elements in this problem situation are the research disciplines and the companies they study. The changing (process) elements are the contents of the research carried out and the contents of the material flow transformed by the company. A root definition of the structural systems should now be formulated.
With van Aken (1991: 9) it is stated that a research discipline can be characterized by it's domain which consists of four elements:

1. the subject-matter of the discipline,
2. the organized body of knowledge of the discipline,

3. the corps of professionals of the discipline,
4. the societal patronage of the discipline.

The point of view taken here is that the organized body of knowledge can be derived from the subject-matter of the research discipline. As stated above, the body of knowledge should be seen as a process element, the subject-matter should be seen as a structural element of the problem situation. Because we look for a lasting distinction between disciplines, the subject-matter of a discipline seems to be a more promising basis than the body of knowledge. An individual company can change but production companies still will be the subject-matter of the discipline. Knowledge can be added to the body of knowledge of a discipline but it can also become outdated and no longer be considered a part of a discipline's body of knowledge.

It seems difficult to strictly define the professional who is working purely in the Industrial Engineering and Management Science area. Students of this area can be found in diverse jobs and work-situations which can hardly be related to IE & MS as a research discipline. The definition of the discipline's societal support seems to suffer from similar flaws. For this reason, the societal patronage and the corps of professionals are not selected for discerning the research discipline.

So, Industrial Engineering and Management Science has to be discerned from other disciplines on basis of a better and more model-like definition of it's subject-matter. The subject-matter happens to be the company: the second structural element in our problem situation. The distinction between different disciplines then is a problem of the division of the subject-matter (a company) over the different scientific disciplines that study it. For this division the W(eltanschauung) of IE & MS has to made explicit. In other words, making a useful conceptual model of the subject-matter asks for an answer to the question how IE & MS in general looks at a company.

The above question can be answered by looking at the views of some of the important representatives of the discipline. This leads to the conclusion that a distinctive characteristic of IE & MS is that it views a company as a set of activities grouped around a physical transformation process in which semi-finished goods (processed natural materials) or parts or composing substances are transformed into products. Typical in this view is the starting-point that a company is a system for making products and that it is asked what more is needed for that goal than just the transformation of the materials/objects (see e.g. Krabbendam (1991), Studiegids TUE 90/91 (1991) and Wijngaard (1991)). From these authors we derive the following root definition:

> 'A company is an integrated system of people and means for the controlled transformation of semi-finished goods and/or parts into products that satisfy the customer's demand for the use, further processing or

consumption of those products whereas this transformation satisfies environmental and internal regulations'.

The completeness of a root definition can be checked by a 'CATWOE analysis' (Wilson, 1990: 72), a checklist of six elements that the root definition should consist of:

- customer: the consumers of the transformation output,
- actors: the performers of the transformation,
- transformation: the core activity of the relevant system,
- W: the view of the role of the relevant system in it's environment,
- ownership: the encasing system that can decide over the relevant system,
- environmental and wider system constraints: the constraints that the system's environment or the encasing system imputes on the relevant system.

In our root definition, the six elements of the CATWOE analysis have been operationalized as follows:

- customer: professional buyers or consumers of the company's output,
- actors: people and means,
- transformation: the transformation of raw materials/semi-finished goods into products,
- W: the view of the relevant system as a producer of products,
- ownership: not specified (!),
- environmental and wider system constraints: the regulations that the company's environment and the people in the company impute on the functioning of the company.

This definition clearly represents the IE & MS view of a company. This view is different from e.g. the judicial view: a company as a legal body with rights and duties and from e.g. the purely economical view: a company as a generator of money for it's owners. In the IE & MS view the ownership of a company is not particularly relevant. For this reason the ownership is not filled in (see CATWOE analysis). This idea seems to be run parallel to the ideas of van Dam (1991). In the figures he uses to distinguish different disciplines in Management Sciences he each time adds a third term to the two terms 'man' and 'organization'. For IE & MS this third term is 'technique'. Because of the view sketched above, in the rest of this article the term production company is used in stead of company.

2. Toward a conceptual model of a production company

From the root definition a conceptual model of the relevant system can now be derived. According to Checkland such a model is found by defining the minimal set of activities, at a certain aggregation level, that the system has to carry out in order to be the system specified in the root definition. The conceptual model should specify what the system should do in order to be the system specified in the root definition (and not how this is done). Activities (a verb and an object) and relations between activities (noun) are the elements of the conceptual model. Clearly, such a model does not specify who/what carries out an activity (a human, a machine, an automat), but it only specifies the activities themselves.

There are three sets of activities a production company has to carry out (see e.g. Schey (1987), Harrington (1985), Kalpakjian (1987)):

a. Transforming activities

This is the stream of objects that is transformed (physically, in time or in space) by the application of energy. This process is usually split up into:

- purchasing[3]: the supply of semi-finished goods that are to be transformed (which can also be former products that are recycled),
- manufacturing: the transformation of objects or materials into objects that satisfy predetermined standards of form and function and that are meant to be a unit of a larger whole,
- assembly: the joining of parts into a product,
- packaging: the assembly of product(s) and packaging materials into a configuration that is transportable,
- shipping: the transformation in space of the packaged products.

Although it is the objective of this thesis to study manufacturing technique from an IE & MS point of view, the complete transformation process will be sketched first.

b. Concretizing activities

The physical stream under a. is embedded in a larger series of activities. Preceding the physical transformation processes, customer demand and production knowledge has to be transformed (concretized) into the specification of a product. This concretizing process is traditionally split up into:

---

[3] Purchasing is seen here as a physical transformation in space.

- conceptual design: the translation of customer demand into product functions,
- lay-out design: the design of a lay-out of the physical product, the choice of concepts for subsystems of the product and the major processes for making the subsystems,
- detail design: the detailing of the product lay-out and the subsystem concepts into detailed designs (on piece part level) of the physical product (considering the main processes and machines to make the product),
- process planning: the choice of processes and machines to make the product and the transformation of the detailed designs for physical objects into manufacturing and assembly instructions .

This total series of activities under a and b., in which the product description is concretized (via design and process planning) and in which materials are transformed (via purchasing, production and shipping), is given in figure 2 (the upper layer represents the activities under a.).

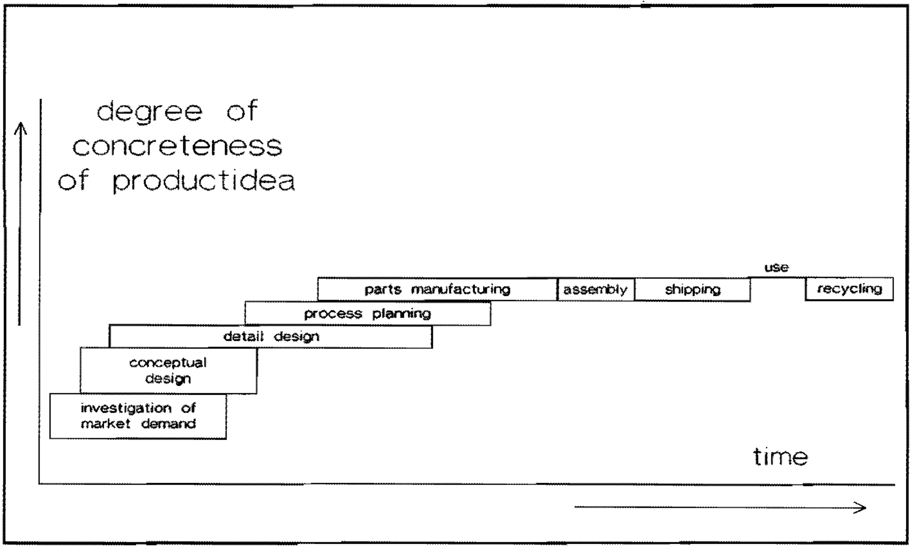

Figure 2. The concretizing and transforming activities in time.

Normally however, in a company these activities are not carried out sequentially for one product but in parallel and for several products. This is given in figure 3.

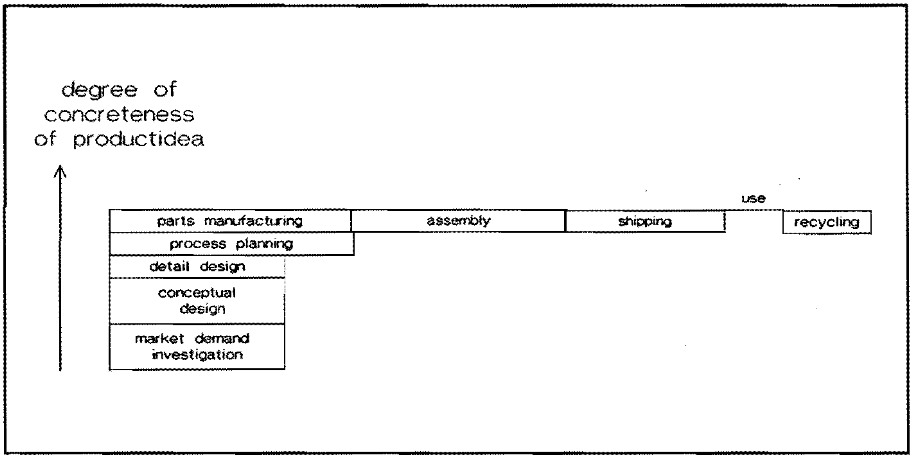

Figure 3. The concretizing and transforming activities.

It should be stressed, though, that it is assumed that the use and the recycling of the products takes place outside the system boundaries (= outside the company). Information about the use and the recycling of products, however, is assumed to be an input to the product design activities.

c. Integrating Activities

For satisfying the root definition the activities under a. and b. are not sufficient. These activities can constitute a static qualitative match between the output of the system and market demands. For changes in the quality of the output according to outside demand and for a quantitative match between demand and supply, a coordination of demand and supply is needed. So, the activities under a. and b. have to be complemented with activities that control the activities under a. and b. (see e.g. in 't Veld (1983)). The output of the activities under a. and b. has to be aligned dynamically with the (future) demand pattern of the environment. This asks for integration of the timing and the contents of these activities (see figure 4). It is assumed that there is a hierarchy of activities that deals with the integration of the activities mentioned under a. and b. (cf. Bonney & Head (1992)).

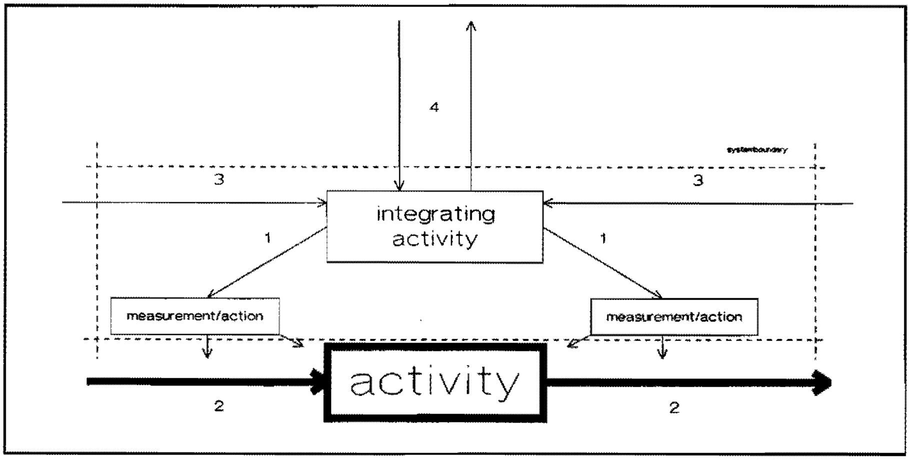

Figure 4. The integration of activities (schematically).

Since this is still the formulation of the conceptual model, the 'how' of the activities is still not of interest. So, in our reasoning, it is not yet important who or what carries out these integrating activities. It is important, however, what these activities do contribute to the functioning of a company. At the lowest level of this integration hierarchy single operations with their inputs and outputs (2) are controlled (1). The next higher level integrates this control of single operations (3,4) etc. The hierarchy ends at the level of 'integration of company output as a whole with the environment of the company'. This hierarchy involves planning activities, commercial activities etc.
The integration hierarchy might suggest some analogy with the well-known distinction between 'operational', 'tactical' and 'strategical' decisions. The latter distinction, however, is often based upon the length of the horizon over which the consequences of the decisions extend or the financial impact of the decisions. Here the criterion is the number of layers that are integrated on a certain level. The length of the period over which this integration stretches is not always long or short.

3. A conceptual model of a production company

Based on the observations above, a company can be modelled in terms of concretizing, transforming and integrating activities. In order not to add another terminology to the field, the first two activities will further be referred to as: design/development respectively production activities.

Below, the conceptual model will be detailed for the manufacturing activity. The technical aspects of mechanical manufacturing and the transformation of functional specifications into manufacturing instructions and tools (design/development activities), are the subject-matter of the Mechanical Technology (MT) sub-discipline of the Mechanical Engineering research discipline. So, it should be possible to find definitions of the manufacturing technique, and of the design/development activities in the terms of MT. Below, these definitions are applied to detail the three dimensions of the company model.

1- the production activities,

As explained above, this dimension has the values: purchasing, manufacturing, assembly, finishing, packaging and shipping of the product. The relations between these activities are the outputs of the foregoing activity: respectively semi-finished goods, parts, products, packed products.
In MT, the manufacturing section of the pipe-line is seen as consisting of three layers (see e.g.: Kals & Houtackers (1988), Lange (1988), Wolffgram (1978), Alting (1982)):

a- the materials layer,
b- the process layer,
c- the machine layer.

a.- The materials layer is defined as: 'the physical objects or materials that are processed'. The objects/materials can consist of metals, plastics or any other type of material. Important is that these are the subjects of transformations leading to the product (part) as desired. The outputs of manufacturing and assembly are defined in a hierarchy as follows:

a product = the materialization of a consumer need
consists of:
functional parts[4] = the materialization of a specific sub-function
consist of:
subassemblies = physical elements of a functional part, consisting of different parts
consist of:
parts = single physical object satisfying predetermined standards of form and function
made of:
semi-finished goods = fluid or solid materials processed to a certain specification.

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[4] These are not per definition single physical parts.

In some cases some of the intermediating steps may not be present. For example, a product can be made of one part. Here, however, the most extensive situation was sketched. The input of manufacturing is considered to be semi-finished goods, the output is considered to be parts.

b.- The manufacturing processes layer is defined as 'the processes which transform materials or objects into objects which satisfy predetermined standards of shape and function'. The processes treated here are mechanical manufacturing processes which are applied in an industrial environment and which are aimed at making geometrically and functionally defined objects. In DIN8580 (1985) these processes are classified as being directed at either:

- creating shape out of shapeless material,
- changing the shape of objects,
- connecting objects,
- fixing layers on objects,
- changing the material characteristics of objects.

These processes will be further broken down into generic elements in chapter 4. Here, however, it is necessary to highlight one element of the manufacturing processes, namely the element that establishes the connection between the manufacturing process layer and the next higher machine layer. This element is the tool(s) in the manufacturing process. A tool is defined as: 'the physical object, the material or the phenomenon which actually forms the material or the object which is to be transformed'.

c.- The machine layer finally is defined as: 'the installations aimed at providing the energy for the process and the capability of moving and positioning tools'. This ranges from simple installations providing transformation energy on the one end to sophisticated Flexible Manufacturing Systems on the other end. However, the function of a machine is not necessarily carried out by an apparatus. A human being can provide this function too. Yet for MT the human operator is not a research subject.

Together, these three layers (a, b & c) enable an operation: 'a change of the characteristics of an object or material by the controlled transfer of energy from a tool to the object during an uninterrupted relative movement of the tool and the object'.

The MT research area can extend beyond the three layers of the pipe-line when the control and integration of operations is automated: the areas of automatic machine control, respectively automatic control of a group of machines, are subject of MT research. But not of MT research alone: the electro-technical aspect of such control problems are so important that this field is commonly called 'mechatronics'. Another two layers can thus be added: 'machine control' and 'control of machine groups'. Again, these layers should not be seen as exclusively belonging to the MT field.

2- the design/development activities,
For the traditional organization of the design/development activities it is referred to the prescriptive model of the design/development process. An overview is given in figure 5 (see also: Voelcker, 1988).

The objective of conceptual design in the prescriptive model is to generate an 'optimal' conceptual solution for the product functions. The process of generating these solutions should be creative and should preferably not be 'blocked' by too many practical considerations (Ullman (1992), Pahl & Beitz (1988), Schierbeek (1988)). Only when the concept variants are evaluated, production aspects of the alternatives are taken into account. This is only done in qualitative terms however. Pahl & Beitz (1988: 135) e.g. give the following guideline: 'few and established production methods, no expensive equipment, small number of simple components'.
When a choice between detailed product lay-outs has to be made, arguments like 'manufacturability', costs and delivery-time are taken into account. In the design process, the choice of detailed lay-outs (in embodiment design) is the first moment that the influence of manufacturing technique truly manifests itself. The time or costs associated with this choice between several technical alternatives can not be allocated to a single technical alternative. Only after the preliminary lay-out has been chosen a specific alternative 'production method' influences the further design process.
In detail design every single part of a product has to specified exactly. This specification involves manufacturability constraints on the geometry of a single part. These constraints are usually specified in design catalogues for a certain manufacturing process (see e.g. Lyman (1962), Mielnik (1991)), or in an expert system for detail design (see e.g. Meerkamm & Finkenwirth (1989), Woodward & Corbett (1989)). The number of these (empirical) constraints dictated by a certain manufacturing process could determine the time needed to process them in detail design. The quality of these constraints, in the sense that they really increase manufacturability of a design, will manifest itself only in process planning. In this stage it comes down to the translation of the detail design into manufacturing instructions. The influence of manufacturing technique (the machine, the manufacturing process) on throughputtime is obvious for this stage.

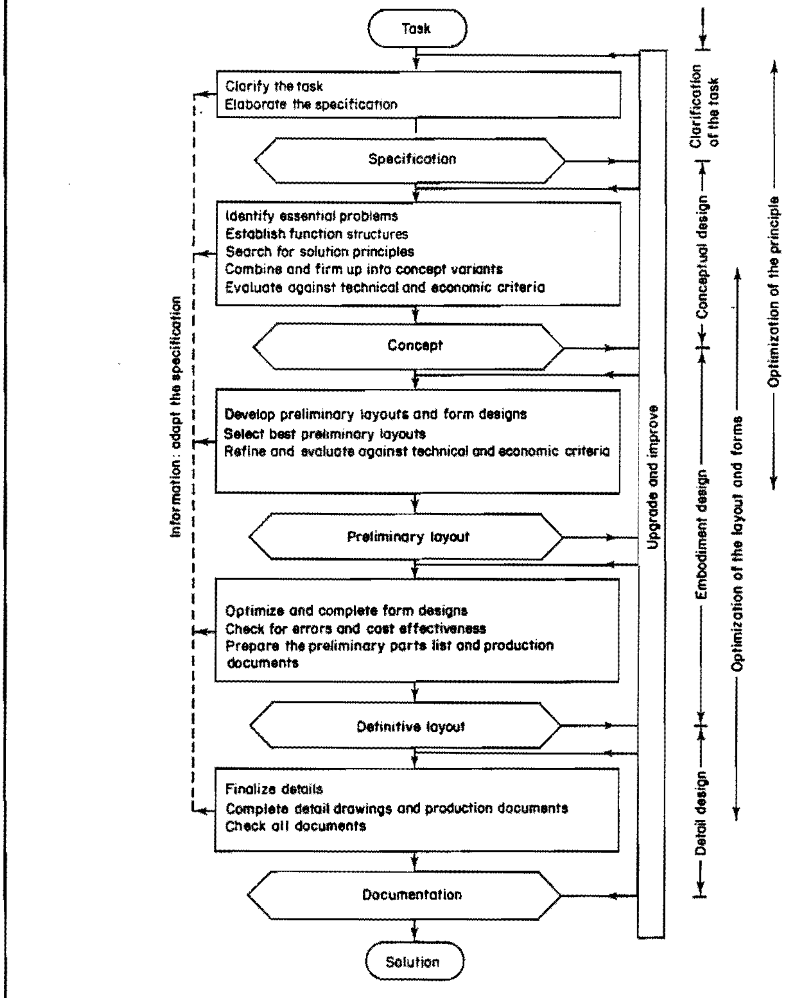


Figure 5. The traditional split-up of the design/development activities (from: Pahl & Beitz, 1988).

In reality most designers do not follow the process as indicated (see e.g. Ullman (1991)). Iterations will take place and precise activities per stage can differ depending on the particular situation (see e.g. Enters (1990)). Moreover, designers seem to choose one concept early in the design process and tend to stick with that concept rather than to consider alternative concepts. Moreover, recent contributions in the literature state that the sequential design process as sketched above results in a long and inefficient design process. The sequential approach typically leads to a behavior in which results of one phase are handed over to the next phase without any previous consultation (Williamson, 1990). For complex designs this leads to long feed-back loops and much rework. Most authors present an approach that is characterized as concurrent or simultaneous design (or engineering). In this approach the different phases in the design process cooperate early on in the design process which creates shorter feedback loops and avoids rework (see e.g. Clausing & Pugh (1991), Riedel & Pawar (1990), Noble & Tanchoco (1990)).

3- the integrating activities,

In respect to the integrating activities, a reasoning parallel to that used in section 1 can be applied. If the design process or the integration of the activities in the design process is automated this also becomes the domain of Manufacturing Technology (MT). However, this domain is not exclusive for MT. Here too, other technical disciplines are involved.
On the lowest level, this is the integration between single steps in the design and development or production activities. On the higher layers the integration takes place between sets of activities and standards from higher levels of integration. This integration involves a.o. logistical and commercial activities.

Based on the detailed description of the dimensions figure 6 can be drawn. The production activities are represented by a pipe-line in which semi-finished goods enter and from which products leave. This pipeline is also fed with manufacturing instructions, tools etc. from the one side (horizontal: design and development activities) and with production orders from the other side (vertical: integrating activities).

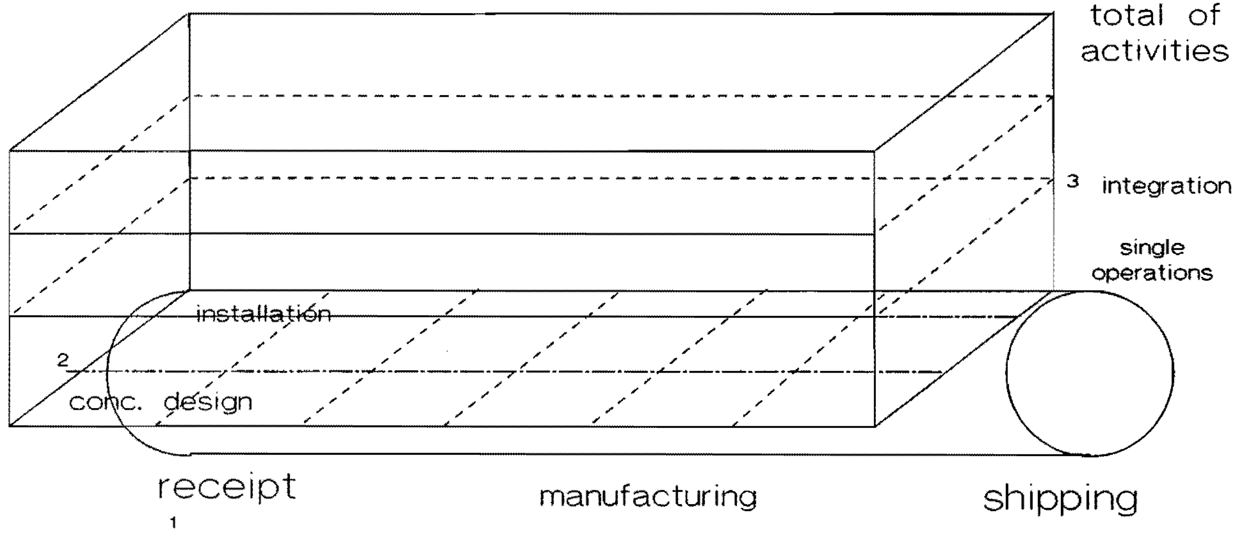


Figure 6. The conceptual model of a production company.

The correctness of a conceptual model of a Human Activity System can be checked by means of the formal systems model (Checkland, 1981). The formal systems model is a set of concepts that have to be represented in a HAS in order to let it fulfill it's function. The set consists of:

- the logical dependence between activities: this is given by the enumerated dimensions,
- raison d'être: this given by the transformation,
- measures of performance, monitoring and control mechanisms, decision-making procedures: these are given by the integrating activities,
- boundary: this is marked by the beginning and the end of the dimensions,
- resources: supporting activities, these are not represented in the model, this is in concordance with the Industrial Engineering and Management Science W,
- systems hierarchy: here one level was chosen.

From the formal systems model we can conclude that the conceptual model above does indeed represent a production company sufficiently well for our purposes. The dimensions chosen are valid because:

- they represent ordered sets: the dimensions have a lowest and a highest value and have an order,
- they are exhaustive: there is a logically determined highest and the lowest value,
- they are independent: a value on one dimension does not exclude a value on the other dimensions.

In a concrete situation several of the activities mentioned will possibly be carried in one department, by one person or will even be contracted out. Over time the division of the different activities over departments or persons can change. Activities can be directed to the whole of another dimension (market research for a new product) or to a part of another dimension (market research for a certain part). These possible variations, however, do not render the conceptual model invalid. It only helps to indicate the general applicability of the conceptual model. What does become clear however is that in a concrete situation the how of the activities becomes relevant too. After the formulation of the conceptual model the determination of how the activities are carried out is an essential part of further analysis and problem solving.

4. The Industrial Engineering and Management Science research area and the other disciplines in Management Sciences and Mechanical Engineering

With the help of the conceptual model the IE & MS research area now has to be discerned from other disciplines in the MS field and from Manufacturing Technology. Going back to the root definition we can see that essential elements for Industrial Engineering and Management Science are:

- integrated system of people and means for production,
- optimal satisfaction of environmental demands (or: improvement of system performance).

This leads to the conclusion that the study of machines, groups of machines or materials as such is not a part of the IE & MS research area. In that case, the human being is not an integrated part of the subject-matter. An example of such research would be the determination of optimal cutting speeds for aluminum.

The contents of the translation of part characteristics into manufacturing specifications (design and development activities) can not be seen as a subject for IE & MS research either. The same argument of absence of the human being as integrated part of the subject-matter can be applied. An example of such research would be the investigation of restrictions that a certain manufacturing process (e.g. casting) puts on the specifications of a part.

So defined the lowest level of the cube and the pipeline are themselves not a subject of IE & MS research. However, the integrating activities in themselves are not automatically suited as IE & MS research subject either. The criterion that the human being has to be an integrated part of the research subject can lead to the exclusion of integrating activities. For example, a man-machine system is a subject of IE & MS research. An automated machine as such however does not include the human being (the operator) and thus should not be seen as a subject for the IE & MS research area. The same goes for the unmanned factory. If such a thing would become reality it would not be a subject of IE & MS research. What then can be seen as a subject-matter for IE & MS research? In view of the company model sketched (figure 6) and the observations above, the IE & MS research area can be described as research of the integrating activities as goal-oriented integrated man/means systems. It is important to note that this does not mean that control activities in the strictly logistical sense are studied. Rather, the integrating activities are observed as a control activity. Because of it's goal-oriented character, looking at the integrating activities from a control point of view is the basic characteristic of IE &

MS. As a consequence of the subject of research, the demand from the environment that has to be satisfied should always be taken into account: control supposes a goal. Thus, IE & MS research will often be aimed at improvements, at increasing the performance of the companies studied.
More specifically this means the study of:

- single man/means systems as control activities,
- the cooperation between persons in integrating activities in relation to the means used,
- the rules that people use in these activities in relation to the means used,
- the information which people need to carry out these activities.

(Later in this text these subjects will be worked out for the activity process planning.)
Clearly, in order to be seen as subject-matter for IE & MS, the specific integrating activities are to be close to, and are to be studied in relation to, the contents of the design/development activities or the production activities. 'Close' here means: not many hierarchical layers away from these activities. Strategic Management research e.g. will study integrating activities in the higher hierarchical layers. Psychology will study individual behavior in a man-means system. Sociology will study the behavior of a group of people in the integrating activities. Both disciplines, however, do not have a control orientation and do not per definition study the integrated system of man and means.

5. A first conclusion on the subject of this thesis

This thesis will present some observations on manufacturing technique from an IE & MS point of view. As was inferred in this chapter, this means that it should study the relation between the technique applied in production and the integrating activities that are close to either the design/development activities for this technique or the production activities with this technique. As specified above the interest of this thesis is to look at manufacturing technique from a IE & MS point of view. This could be done for any of the production activities (manufacturing, assembly). In this project it was chosen to concentrate on the technique in manufacturing. Another choice would have been possible. However, the importance of manufacturing in total product costs was amongst the reasons to choose for concentrating on manufacturing.

From the sketch of the contents of manufacturing technique it is concluded that the subject for this thesis should consists of an investigation of the links between on the one hand manufacturing processes and material or machines or automation (this is manufacturing technique) and on the other hand (the cooperation between) human beings (experience, training, motivation, information demand) in integrating activities. Such investigation will be directed to improvement of the performance of the system studied.

Before further choosing a specific subject, however, it seems necessary to further explore the relevance of the different production and design/development activities for IE & MS and the extent to which these activities already have been investigated in relation to manufacturing technique. This will be done in the next chapter.

CHAPTER 2.

Process planning and manufacturing technique: relevance and first structuration.

Only by taking into account demands that the market and/or the society in the developed (industrialized) world nowadays put on the design/development and production activities, a relevant research subject can be chosen. Since this thesis aims to explain IE & MS aspects of manufacturing technique, an overview has to be given of the competitive criteria for the manufacturing activities and the design/development activities. By reviewing the literature in this way, the thesis can also be embedded in existing research in the Industrial Engineering & Management Science field.

Section 1 sketches the general developments of the competitive criteria for some important industrial sectors in the western industrialized world. In section 2, the consequences of these trends for manufacturing are treated. Production organization and production control are introduced as the two instruments with which a company can try react to the developments in competitive criteria. These instruments are reviewed by looking at one organizational design philosophy (sociotechnical design) and three important production control concepts: OPT, KANBAN and MRP. It is shown that sociotechnical design, as well as the control concepts, approach manufacturing on machine level.

Then the changing performance criteria for the design/development activities are analyzed. Concurrent Engineering is presented as an instrument to respond to the changing demands. Process planning is chosen as the specific design/development activity to focus on in further research. Sections 3 and 4 analyze the role and tasks of process planning. The automation efforts for process planning are discussed in section 5. In section 6 process planning is viewed as a control task. From this analysis it is concluded that process planning can execute it's control task through the determination of material specificontrol in production only (see e.g. Pischetsrieder, 1991). Consequently, there is a growing attention for quality planning relative to quality control. The Japanese industry is often mentioned as an example of the attention for quality in design and the resulting industrial success. Two techniques are to be mentioned in this respect. The first is Quality Function Deployment: a technique for translating customer requirements into product quality requirements and for further planning the requirements into product specs and into manufacturing instructions (see: Hauser & Clausing, 1988). The second are the Taguchi methods for Quality Engineering: an integrated system of design for quality and on-line quality control. Central in Taguchi's approach is the idea that a high quality product is not a product that satisfies tolerances but a product that is designed to satisfy customer demand under all possible conditions of use: so-called 'robust' products (see a.o.: Taguchi, Elsayed and Hsiang (1989), Taguchi & Clausing (1990)). Both these techniques are important elements of the so-called Total Quality Management (TQM) approach (e.g. Sondermann & Leist, 1989). This approach stresses that attention for quality is necessary through the whole cycle of product design, development and production.

Time

In recent years, the idea of 'time based competition' was developed (a.o. Simon (1985), Berger (1985)). Time based competition is the idea that the control of delivery time throughout the whole supply chain of procurement, production, transport, wholesale etc. is the means of competing in the marketplace of today. Given the product specifications, rapid delivery throughout this whole chain enables proper reaction to changing market demands without excessive inventories (and consequent costs).

Innovation

In many industrial sectors nowadays, short product introduction time is an increasingly important source of competitive advantage. Profit Impact of Market Strategy (PIMS) data (in: Spur, 1991) show that product pioneers have an average ROI which is higher than that of companies pursuing a follower strategy. Other data (in: Spur, 1991) show that an increase in development time of 6 months, in average has a negative effect of 30% on returns, while an increase in development costs of 50% has only a 5% negative effect. It is not surprising then that Kumpe & Bolwijn (1990) describe the 'factory with a future' as a factory in which design and manufacturing are tightly coupled with short throughputtimes. This is yet another reason to focus on the design/development activities.

1.2 Market Constraints

As stated earlier the validity of the four criterion model of Kumpe & Bolwijn (1989) can be questioned. What happens when a company has strongly improved it's price-level, quality, delivery-times and innovativeness? It seems that in a market with several companies each offering several high quality, and innovative products the 'old-fashioned' price-battle will start again.
It should also be pointed out too that market demand in the western industrialized world not only asks for cheap, better and new products. A lot of examples of socially or environmentally inspired demands on products and production processes can be found. Specific coffee brands e.g. label their product as produced under socially acceptable conditions. The ban on phosphates in detergents is an example of environmentally inspired demands. These examples learn that not only market demands but also wider societal demands need to be taken into account when discussing manufacturing technique. Here, however, it is assumed that such demands either result in a complete ban on a certain product or production process or in a higher price for the inputs (e.g. energy) for the product or process. Again, design can play an important role in enabling product recycling.

2. Existing instruments for the manufacturing activities and for the design/development activities to cope with the changing competitive criteria

2.1 Introduction

Given the competitive criteria sketched above, several questions now have to be answered. First, are there any clearly defined managerial instruments to cope with these criteria? Second, at which level do these instruments observe manufacturing technique (material/process, machine, automated machines)? Third, what are the variables that are used to describe the technique at each level?
These questions are answered in the following sections of this chapter.

2.2 The instruments for manufacturing

In this section it will be discussed how the performance criteria sketched above are coped with in manufacturing. With Thompson (1967: 13) it is argued that:

'open systems subject to norms of rationality seek to seal off their technological core from environmental perturbations so as to facilitate optimal planning of operations'. In other words, it is assumed that management will apply certain instruments to protect the company's manufacturing operations from outside irregularities. Such protection can be effectuated through two interdependent instruments: production organization and production control. The requirements posed on manufacturing by the market are filtered by the organization and the control philosophy of the company. Of course, both fields are far too large to be covered extensively in the framework of this thesis. Consequently, only a selection and a short description is given below.

Manufacturing Organization: sociotechnical design

The philosophies on manufacturing organization and technology can roughly be divided in two streams: the comparative approach and sociotechnical design (see: Gerwin (1981) for an extensive overview). According to Gerwin, the main difference between the comparative approach and the sociotechnical design approach lays in the design orientation of the latter versus the assumption of 'biological' causality between organization and technical means of the former. In other words, comparative analysts view management as passive entity, the design oriented sociotechnical researchers try to define the freedom of choice that management faces and the implications of the choices that management makes concerning organization structure. Since the focal point here is the active role that management plays in applying technical means, only the sociotechnical approach will be discussed below.

A prominent author in the sociotechnical design field is Woodward (1958, 1965, 1970). Although her earlier work (1958, 1965) can be labeled as comparative, her later work (1970) was clearly sociotechnical. On basis of a study of approximately 80 manufacturing firms in south-east Essex, she claims to have found a relation between characteristics of the technology (of the production system) and the organization structure of the firms. In a revised version (Woodward, 1965) of the original study she uses a three-category technology scale which consists of: unit and small batch, large batch and mass, process. In her later work (1970) however, Woodward admits that these relations were clear only on the extremes of her scale, indicating that there is considerable freedom of choice concerning structure in the middle.

Lawrence & Lorsch (1967) compare the technology and structure of more and of less successful firms. They find that a firm, to be successful, should differentiate internally corresponding to the differentiation of the markets of the different parts of the firm. However, a differentiated firm must use integrative, coordinative mechanisms to perform effectively. The technology must fit this differentiation.

Galbraith (1973) views 'task uncertainty' as the main determinant of organization design. Task uncertainty is defined as (1973: 9): 'the difference between the amount of information required to perform a task and the amount of information already possessed by the organization'. According to Galbraith, increasing uncertainty leads to increasing information processing demands which, at a certain point, can no longer be handled by the specific organizational unit. In order to be able to cope with uncertainty, an organization's design can be adapted in the following four ways:

1- by creation of slack resources,
2- by creation of self-contained tasks,
3- by investment in vertical information systems,
4- by creation of lateral relations.

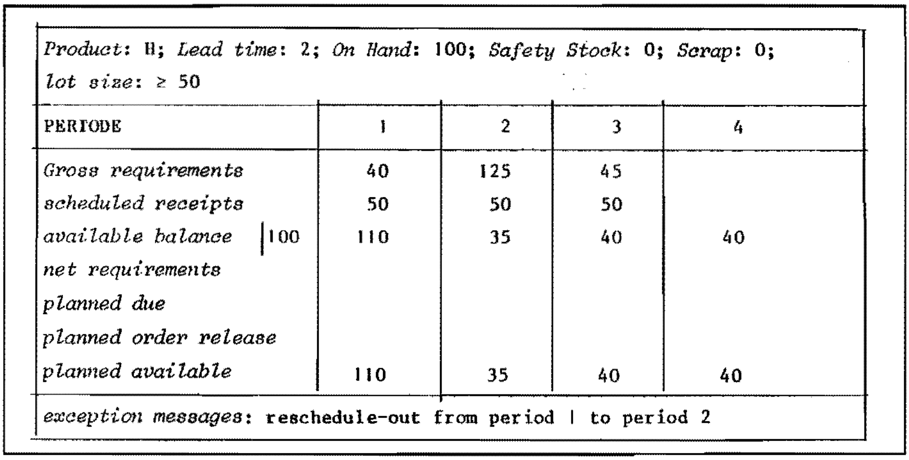
So, the technical means should be judged on their contribution to task uncertainty and their fit to organizational designs that counter this uncertainty.

De Sitter et al. (1986) stress the creation of self-contained tasks and the creation of lateral relations as organizational measures to increase the manufacturing flexibility. According to these authors, a manufacturing organization consisting of parallel product streams (oriented to serving e.g. a specific market or product), that are split up in production groups with self-contained tasks, is robust against outside disturbances like rapidly changing market demands. Recently, Hoevenaars (1991) and Van Amelsfoort (1992) presented support to this theory and developed further instruments to optimally structure manufacturing organization.

From this short overview of sociotechnical design it becomes clear that this approach is well developed. Instruments for sociotechnical design exist. The level at which manufacturing technique is observed is the level of machines (or manufacturing resources). Generally, this approach favors manufacturing resources with a relatively small capacity. Such technical means facilitate the formation of small self-contained task groups that concentrate on a specific set of tasks. Heavily integrated manufacturing lines are less likely to facilitate this.

Manufacturing Control Concepts: KANBAN, OPT and MRP

Generally speaking, there are three well-documented production control concepts in the literature: KANBAN, MRP and OPT. Although these concepts are not especially suited for small batch manufacturing all three concepts will be discussed here. This discussion of the three most important production control concepts starts with Material Requirements Planning (MRP). MRP is a theoretically well developed and relatively old concept. The operationalization of production units in it, can be derived from the MRP calculation schemes (Orlicky, 1975) (see figure 2).



Product: H; *Lead time*: 2; *On Hand*: 100; *Safety Stock*: 0; *Scrap*: 0;
lot size: ≥ 50

PERIODE		1	2	3	4
Gross requirements		40	125	45	
scheduled receipts		50	50	50	
available balance	100	110	35	40	40
net requirements					
planned due					
planned order release					
planned available		110	35	40	40

exception messages: reschedule-out from period 1 to period 2

Figure 2. The MRP scheme (from: Orlicky, 1975).

The attributes in the MRP scheme that are related to production means are:
- scrap factor (the percentage of scrap that production is expected to make),
- lead time (the time to make a lot size using these production means),
- lot size (which is determined by set-up time of the production means and the costs of keeping inventory).

Safety stock is not considered as an attribute of the production means since this is mainly determined by expected variance in demand. The schemes themselves are based on a particular product structure (every part and subassembly in principle has it's own scheme). This product structure is reflected in the Bill of Materials which indicates a production structure as well: certain routings are assumed. In a separate capacity check, the total capacity of a production unit, in a certain time-span, is checked against demand.

Another production control concept is KANBAN (e.g Shingo, 1982; Durlinger & Wortmann, 1983). In this concept production departments or -stations determine the production schedule of production-departments or -stations 'upstream' by means of regular transfer of information on what was used in producing the demanded products. The downstream departments fill up the used quantities in short cycles. Figure 3 illustrates the functioning of this concept.

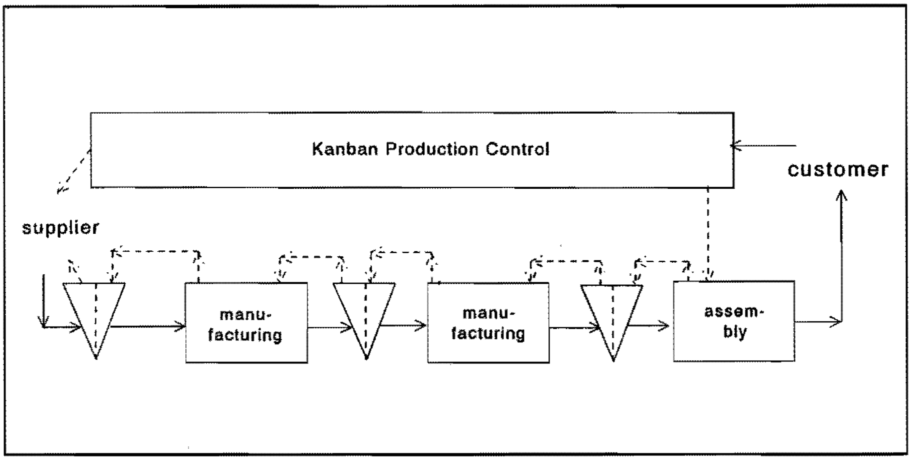


Figure 3. An illustration of the KANBAN principle.

Such a concept assumes that manufacturing resources can be set-up rapidly for any manufacturing operation in the specified range. Because of the tight linkage between operations in the system, the individual operations should work with 'zero defects' as well.
The production control concept 'Optimized Production Technology' (OPT) (e.g. Goldratt & Cox (1986), Fox (1984)) centers around the idea of 'bottlenecks'. A bottleneck is a production resource (generally: a machine) that limits the output of the total system (generally: a factory) because of it's limited capacity. The idea is that, by maximum loading of the bottleneck, the total output of the system can be maximized. The amount of capacity that a bottleneck has is calculated by summing the time needed for manufacturing operations, the set-up times for the different products and by allowance for the scrap-factor.

From this short overview it is clear that there are at least three theoretically well developed instruments for production control and that these instruments all observe manufacturing at machine level. For KANBAN, like for MRP, the set-up time, the time needed for a manufacturing operation and the scrap-factor are the important aspects of the machine. However, KANBAN makes stronger assumptions as to the balancing of capacities in a production line and the tight linkage of these capacities. This implicitly asks for very reliable resources operating in parallel. Such a claim is not made in MRP. In OPT too these three factors are the aspects in which the manufacturing means, i.c. the bottle-neck, are operationalized.

In other words, in these three production control concepts results (in terms of system output), and/or the ease of production control, can be increased by:

- reducing set-up times,
- increasing production rates,
- increasing the indifference of resources for different types of products,
- reducing scrap-factors.

In the increasingly vehement competitive environment that most production companies face, this led to a drive for increasing production flexibility both in product-volume and -mix. From a technical point-of-view this meant that ways to achieve the changes mentioned become increasingly important. A frequently cited example in this context is the TOYOTA production system where the JIT production philosophy (which includes the KANBAN control concept but also a specific approach to quality and even marketing) established the drive to bring down set-up times of presses for car body panels. As these set-up times were still measured in terms of hours in the West, the Japanese brought set-up times down to a few minutes. The definition and measurement of flexibility as well as it's relevance relative to other performance measures have become important themes in the literature (see e.g.: Dirne (1990), Buzacott (1989)).

2.2 Instruments for the design/development activities

The increased speed demanded of the design/development activities (see section 1.1.4) led to the development of the concept of 'concurrent (or simultaneous) engineering' (Eversheim et al. (1985), Noble & Tanchoco (1990), Clausing (1991)).

Clausing (1991) views the design/development process of a product as consisting of six phases:

- Total System Concept Design,
- Subsystem Design,
- Piece Part Design,
- System Verification,
- Production Preparation,
- Pilot Production.

In phase two, Subsystem Design, tools like Fault Tree Analysis, Failure Mode and Effect Analysis and Parameter Design (see: Taguchi & Clausing, 1990) are used to determine a conceptual lay-out of the subsystem. Also, the critical characteristics of the subsystem (functional and safety requirements, interfaces with the rest of the product) are given.

The choice of the manufacturing processes with which the parts of the subsystem are to be made determine the material, the exact shape and performance, and the costs and delivery-time of the parts. So, process planning for parts with a dynamic status (i.e. parts that are to be newly developed) and with critical subsystem characteristics has to start during subsystem design. After the choice of manufacturing processes for a subsystem, most of the parts in a subsystem can generally be developed by individual detail designers and by individual process planners with existing aids or even with an automated process planning system. For some parts, however, the experience and the means available to the individual designer/planner will be insufficient. Such parts have to be developed by a development team.

Clausing & Pugh (1991) present the concept of Enhanced Quality Function Deployment as a means for communication and decision making by such a team. The detailing of translation steps is done in matrices. The dimensions of the axes of the matrices are given, the team members specify relations between these dimensions by filling in the matrices. The team decision making is also supported by appropriate data-bases. Figure 4, a revision of Figure 2 of Clausing and Pugh, shows the process of Enhanced Quality Function Deployment (EQFD) graphically.

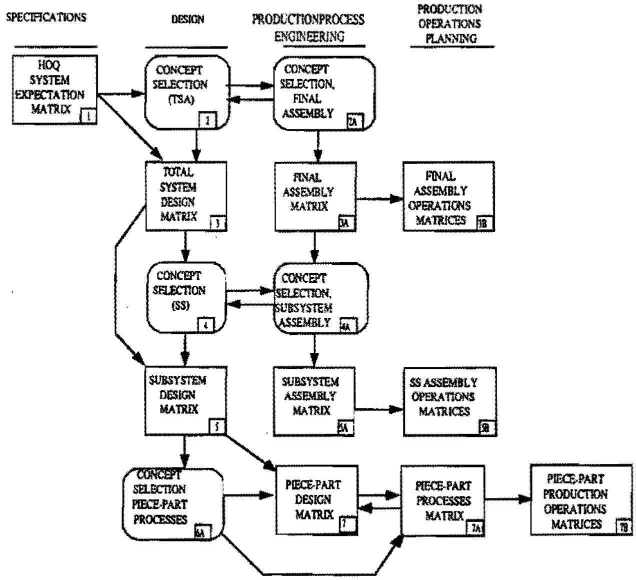


Figure 4. The process of Enhanced Quality Function Deployment (from: Clausing & Pugh, 1991).

The so-called 'House of Quality' (HOQ, figure 4 above left) is a matrix in which market demand (or: 'voice of the customer') is translated into the total system expectations (in engineering terms). This means that every wish of the customer is translated to a value for it's realization in the product. If, for example, the voice of the customer is: 'door should open easily', then a specific value of the force needed to open the door is specified in the HOQ matrix. The total system expectations are then translated to subsystems (Total System/ Subsystem Matrix) and parts specifications (the Subsystem/Piece Part Matrices). If these translations do not lead to existing subsystems or parts, an intermediate step of conceptual selection is necessary. The choice for a suspension function could be between e.g. the concepts 'hydraulic', 'leaf' or 'air compression'. Such an intermediate step is aimed at finding an optimal conceptual solution for the design requirements. It anticipates the downstream design/development phases and thus helps to minimize costs and problems downstream in the design/development process (process planning and production).

In Concurrent Engineering (CE) the development of products and processes is carried out in parallel as much as possible. In the traditional functional organization, and in the traditional sequential design process, the different design and development functions are separated. This leads to a situation in which the next function only discovers difficulties or mistakes of the earlier function after this function has carried out all the work on the specific product. Concurrent Engineering should lead to anticipation and shorter iteration loops in the design/development process, thus leading to quicker reaction on unexpected or difficult tasks.

From the above description it is clear that CE is not yet an instrument that has been developed as far as the production control concepts. Different authors still define the concept differently. The interfaces between the diverse steps are not yet clearly defined. What is clear, however, is that manufacturing technique is observed at both the machine level and the process/material level. A set of variables that fully defines a manufacturing process should ideally be available, since all variables normally have to be specified.

2.3 Conclusion

In general it can be concluded that the thinking on how the manufacturing activities can cope with the competitive criteria is well developed in the literature and has led to some established concepts and philosophies.
As can be expected, the production control field uses the amounts of time needed for different manufacturing operations as main aspects of the manufacturing function. The manufacturing function is almost exclusively observed at machine level and it is seen as a source of capacity i.e. an amount of time that:

- can be spent on different sorts of transformations,
- is partly consumed by 'undesirable' activities like set-ups, maintenance, production of wrong products.

The experience with a concept like concurrent engineering in the design/development activities has not yet resulted in a widely accepted approach like the production control concepts and their applications. Concurrent engineering seems the answer for design/development under tight competitive criteria but the approach is still developing.

So, from the short overview of market demands and their influence on manufacturing activities and design/development activities it can be concluded the organization and control of the latter activities is both gaining more attention and has not been exploited as extensively in the literature as the control and management of the manufacturing activities. It can be concluded too that detail design and process planning are the concretizing activities in which the influence of specific manufacturing techniques is most prominent. This is even stronger for process planning than for detail design. For discrete products that are produced in small series, an important part of the product introduction time is spent on process-planning activities (i.e. the translation of product data into manufacturing instructions and tools). Almenraeder (1983) states that 47.7% of the relative throughputtime of such products is spent in the 'vorgelagerte Produktionsbereiche' (= detail design and process planning). Hebbeler (1989) even presents a figure of 55%, roughly half of which is spent on process planning (see figure 5).

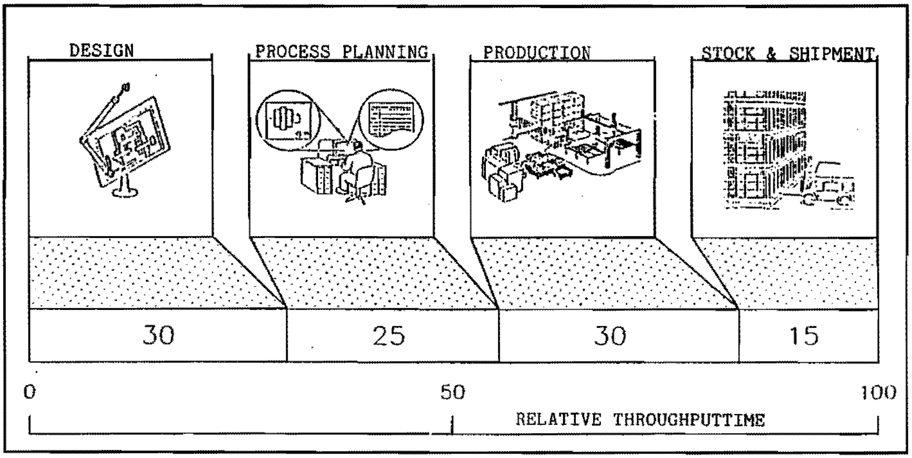


Figure 5. Throughputtime in the different stages of design/development and production (from: Hebbeler, 1989).

Since process planning is also important from a cost point of view (see e.g. figure 1), this activity is an interesting candidate to focus on in further investigation.

3. Process planning in the context of the design process

According to the AWF (Ausschuss für Wirtschaftliche Fertigung e.V.), process planning consists of "all non-recurring planning activities which enable the manufacturing of a product within economic constraints" (in: Spur & Krause (1984), translation by the author).
As discussed in chapter three, in the traditional approach to design the input to process planning comes from detail design. This input usually consists of:
- engineering drawings of single parts and of their assemblies,
- the bill of materials for assembly,
- order data (e.g. order quantity).

The output of process planning usually consists of:
- a process plan: the instructions for the necessary manufacturing operations,
- a quality control plan: a statement how to measure part/product quality,
- NC program(mes),
- drawing of the specific manufacturing means (tools, fixtures).

Clearly, the main task of process planning is the translation of the product information into instructions for manufacturing that enable the making of the part. Apart from the order data, the part information in the input is mainly geometrical. The name of a part and the drawing also says something about it's function but formal functional information normally is not present (Kargas et al., 1988). This geometrical information has been determined in detail design on basis of the function of the product/parts. The functional shapes are not always manufactured as such by a single manufacturing process. The functional geometry and other functional specs. have to be broken down and/or translated into specifications that are to be manufactured by a certain manufacturing process (Grabowski & Seiler, 1985). This break-down/translation consists of a break down of the total part information into different 'manufacturing features'[2] that each are to be manufactured by different processes or different process steps (Patel & McLeod, 1988). So, part shape, tolerances etc. have to be translated into features that have a meaning for manufacturing (i.e. into features to which process capabilities, process constraints and machining parameters can be related). Shah (1988) calls this 'feature mapping'. So, features that have a certain meaning in the design domain have to be mapped to features with a meaning for manufacturing. After the mapping, the manufacturing features are to be translated into values of the manufacturing

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[2] = 'information sets ' that refer to aspects of form, or other attributes of a part, such that these sets can be used for reasoning about the manufacturing of the part (Shah, 1988).

process variables. In case the design features can be translated into manufacturing features only with great difficulty, iteration between the mapping and the translation step can be necessary. These problems and the mapping process will be treated in more detail later on.

4. The tasks of process planning

Several authors give listings of the tasks which are generally carried out in process-planning. Often a differentiation in short-term and long-term tasks is made. An overview is given in table 1. It is assembled from the listings given by Goswami (1973), Baberg (1980), Almenraeder (1983), Spur & Krause (1984), Hebbeler (1989) and Van Houten (1991).

Table 1 The tasks in process planning as found in the literature

short-term tasks

- receipt and interpretation of part/product information
- check of part manufacturability*
- specification of the manufacturing and assembly b.o.m.
- determination of processing sequence
- NC programming
- determination of set-ups
- determination of auxiliary materials
- determination of process conditions
- specification of manufacturing instructions
- calculation of processing-times
- standard price calculation
- selection of machine tools
- decision on the making of specific tooling
- specification of (specific) tooling
- decision on the making of specific fixtures
- specification of fixtures
- specification of quality control instruments
- instruction for quality checks
- carrying out of test-runs
- rework on tools or instructions
- release of parts to production
- instruction to design

long-term tasks

- planning of manufacturing means
- planning of storage type and location
- development of manufacturing methods
- development of planning methods

* = technical and economical considerations

This general picture of the process planning tasks was studied in three factories, all manufacturing sub-assemblies/parts for the avionics industry. The objective of this empirical study was to get an impression of the influence of the manufacturing processes and resources applied on the importance and order of these tasks. All three factories are part of the same company. This eliminates company specific influences when the tasks of process planning in the three factories are compared. The three cases are sufficient for the conclusions that are to be drawn. Each case represents a different category of manufacturing processes (see DIN8580). Moreover, the objective of the empirical study is a comparison with the literature, not research results that can be interpreted independently.

Case 1 is a factory which produces aluminum parts. The main manufacturing process in this factory is milling. Case 2 is a factory which produces parts and subassemblies of synthetic material. The main manufacturing process is laminating (= the production of three-dimensional shapes by clothing a mould with strips of hardening synthetic material). Case 3 is a factory producing parts from sheet metal. The main manufacturing process here is pressing.

The tasks in process planning in the three factories were found by means of interviews with process planners. In the interviews the process planning tasks for three parts (per factory) were tracked. The long-term tasks of process planning as well as possible scheduling tasks were not taken into account. By comparing the results for the three parts the tasks could be mapped. Table 2 gives an overview of the tasks in process planning for each of the three factories.

As can be seen in table 2, the tasks can be clustered in four groups:
- writing manufacturing instructions (incl. the choice of manufacturing resources),
- design & manufacturing of specific tooling & fixturing,
- calculation of processing-times,
- production start-up and possible feed-back.

This is in agreement with the tasks reported in the literature mentioned above. However, the sequence of the tasks and their status differ from case to case. In order to get a better picture of the influence of manufacturing processes and resources on the tasks in process planning, the tasks will now be worked out in more detail for the three cases.

Table 2. Schematic view of the process planning tasks in three factories.

	CASE 1	CASE 2	CASE 3
1	writing manufact. instructions, determine if specific tooling is needed	definition and design of specific tooling, planning of tool-manufacturing	writing manufact instructions, determine if specific tooling is needed
2	(if NC machine) NC program writing, (if spec. tooling) in parallel: design and order of tools	order tools, in parallel: writing manufacturing instr.	(if NC machine) NC program writing, (if spec. tooling) in parallel: design and manuf. of tools
3	calculation of processing-times, define quality-meas. instructions	check delivered tools in parallel: define quality meas.instr., calculation of stand. processing-times	calculation of stand. processing-times, define quality-meas. instructions
4	(if new part) test-run and inspection	(if new part) test-run and inspection	(if new part) test-run and inspection
5	(if necessary) feed-back on quality to tooling or instr.	feed-back on quality to tooling or instr.	feed-back on quality to tooling or instr.

Task 1 Writing of manufacturing instructions:

In all three cases this task was carried out starting from engineering drawings and a parts' list. The choice of the manufacturing processes for the part had been made outside process planning. As said, the manufacturing instructions have to be made for every manufacturing operation of every single part. Before this can be done the machine on which the process is to be carried out has to be chosen too. So, for a certain manufacturing process, the difficulty of this task is mainly determined by the freedom of choice in machine selection and the number of operations in the manufacturing route chosen (see Florusse, 1992).

The manufacturing instructions can be oral, written and/or in the form of a NC-program. The instructions are partly directed to a machine and partly directed to operator(s). The format of the machine instructions as well as the importance of the machine instructions relative to the operator instructions, depend on the degree of automation of the specific machine.

Task 2 Design of tooling/fixturing and manufacturing of specific tooling/fixturing:

Specific tooling can be split up in specific manufacturing tools and specific fixturing tools.

Whether or not specific manufacturing tools are needed depends on the characteristics of the manufacturing process. In case 2 as well as in case 3, specific manufacturing tools have to be made for every different part or part type. The available information are engineering drawings of single parts. These have to be translated to tool specifications by tooling design. This gives a second (double) feature mapping step in process planning: from design features to tool design features to tool manufacturing features. Consequently, for these manufacturing processes the capacity needed for designing a specific manufacturing tool will likely depend on the parts' characteristics.

In case 1 generic tools can almost always be used and the decision to make specific tools is mainly based on economic criteria. Tools are specific because the parts' shape is built into them. The manufacturing of the specific tooling is done by a special tool making department (case 2) or an outside company (case 3).

In case 1 (main manufacturing process milling) most parts can be made with available manufacturing tooling. 'Tooling design' here mainly is a selection problem and a problem of optimizing tool availability for all parts in the factory.

Whether or not specific fixturing is needed depends on a combination of the fixturing aids of the specific machine and technical (tolerance, surface roughness) or economical criteria. In case 1 a vacuum system is used so the raw material should have at least one big enough, and perfectly flat, side.

Task 3 Calculation of processing-times:

In all three cases, the calculation of process times was a minor contribution to the capacity demand in process planning. In case 1 the calculations were even carried out automatically from CAD information. It is remarkable though that in the other factories this was a specialists' task.

Task 4 & 5: Production start-up and possible feed-back

In the three cases of table 1, test-runs are only carried out when processes are planned for entirely new or strongly redesigned parts. In other words, dependent on the newness of the process relative to the specific part, test runs are carried out.

Over all the three cases it was found that if product specific tooling has to be manufactured, this accounts for about 80% (with a minimum of about 50% and a maximum of about 95%, see: Florusse 1992) of the process planning capacity demand for a subassembly (see also: El-Gizawy et al., 1989). Moreover, in the situation where manufacturing processes need specific tooling, the sequence of activities in process-planning changes: compare the second case with the first and third.

Hayes et al. (1989) draw similar conclusions from protocol studies of process planners. They find that process planners tend to concentrate on the tasks that determine most of the manufacturing costs. After a first determination of the process plans they tend to go back to the plan and optimize the cost determining factors. After that they carry out the other tasks. If specific tooling is involved this is often the cost and delivery determining factor. In case of generic tooling the number of set-ups (each time the fixturing of a workpiece is repositioned is considered to be a new set-up) often is the cost determining factor. So, then the process planner will concentrate on minimizing the number of set-ups.

The first task, writing of manufacturing instructions, is carried out per part, per manufacturing process. In capacity terms, this task is second in importance to the making of specific tooling. If the influence of the individual manufacturing processes is assumed constant, the capacity for this task seems to depend on the number of operations needed for the transformation of the raw material into the part. This is directly comparable to the number of set-ups.

5. The automation and formalization of the process planning function

For about twenty-five years now, researchers have been working on the automation of process planning. So-called CAPP (Computer Aided Process Planning) systems have been developed for different application areas. In the development of CAPP systems three approaches can be discerned: variant CAPP, generative CAPP and knowledge based CAPP.

Early developments involved variant CAPP based on the idea of group technology (see e.g. Mitrofanov (1960), Loquet (1976)). The idea is to store process-plans and retrieve them (by means of a classification code) in case a comparable part is planned. The adaptation of the old plan for the new part should reduce the amount of (routine) work that would be necessary without this reference to the earlier made parts. An important advantage of variant CAPP is the large application area. This is restricted by the mechanism to relate parts, not by domain knowledge (in the form of 'process laws') for a certain process.

More recent work involves generative CAPP. This means the CA generation of a process plan based on domain knowledge of the manufacturing process. Examples of such generative systems are: APPAS (Wysk, 1977), XPLANE (van 't Erve, 1988) and PART (Van Houten, 1991). APPAS is one of the first generative systems and is capable of selecting multiple processes for a machined surface. It also determines feed rate, cutting speed, tool specifications and the length or depth for each tool pass. In PART, like in XPLANE, after feature recognition, operations are mapped on the features by means of a search tree for every feature. This tree holds all possible operations to manufacture the feature. Operations are chosen using a search algorithm. The feature recognition in PART however is far more flexible than in XPLANE. In PART feature recognition is based on (about 60) atomic features and on (user definable) compound features. Compound features are build from atomic features and have specified machining methods.

Another recent development is knowledge based CAPP: the application of Artificial Intelligence in process planning (see e.g. Gupta & Ghosh (1988), Cheung & Dowd (1988)). In such systems the knowledge used does not strictly have the character of 'laws', something that is required in generative CAPP. In knowledge based CAPP, process laws can be added with less structured knowledge of experienced planners. This results in a rather unstructured body of knowledge. The 'unstructured' character of the process knowledge in knowledge based CAPP can be seen as an advantage as well as a disadvantage. The maintenance of the domain knowledge is tedious. Hayes, Desa & Wright (1989) e.g. base their 'design suggestions' on knowledge derived from the analysis of process plans by experienced process planners. However, they also conclude that the 'particular process plan used depends on the manufacturing resources available, company practices, etc. So, the rules they derive depend upon many local factors and do not represent stable knowledge. In the long run more formalized knowledge of the process seems to be a more versatile bottom for automation.

In the automation of process planning, the translation of the design information to manufacturing information, referred to above, has to be automated too. An automatic process planning system should be able to recognize design features, to map these design features to manufacturing features, to relate manufacturing process variables to these features and to choose machines for these processes (Pratt, 1984). One way to do this is to ask detail design to design directly with manufacturing features: feature based design. An example of that approach for

casting is given by Woodward & Corbett (1989). The designs that are generated in this way can be directly interpreted for manufacturing purposes. The disadvantage of this approach however is that the designer is restricted in his/her possibilities by the predefined set of features that can be used to make the design. An alternative approach is that design features have to be recognized interactively or automatically.
An important problem in feature recognition is pointed out by Shah & Rogers (1988). He defines features in feature spaces with three dimensions: application area, level of abstraction, and product type. Feature spaces can partially overlap, can be conjoint or can be disjoint. In other words a feature for one manufacturing process does not have to have the same meaning for another process or might even be meaningless for another process. So the mapping of design features to manufacturing features is process specific. In the CAPP system PART (Van Houten, 1991) this mapping is done by reading in the part information in an internal representation which is subsequently recognized in terms of 'manufacturing features'. These manufacturing features (±60) are standard features plus features defined by the user and form the primary source of data input to the system. The features represent geometrical/technical entities for which process planners know manufacturing solutions.

6. Process planning as a control task

In chapter 1 it was concluded that Industrial Engineering & Management Science observes integrating tasks as control tasks. For structuring the closer consideration of process planning, here this task will be seen as a control task in which, for each part specification, technical manufacturing variables are manipulated such that the semi-finished good is transformed into a part as specified. So, process planning as a control task has a control variety consisting of the variables of the three layers of the technical hierarchy. This is depicted in figure 6.

Process planning, or another function, has to choose the manufacturing processes for making a part (or subsystem). The costs, time etc. for this choice can not be allocated to the process that is finally chosen. For this choice, however, it should be known what the consequences of each of the alternative processes are. So, process planning is observed here after the processes have been chosen. The criteria in process choice will normally be the following (see also section 1 and Van Luttervelt, 1991)):

1. technical criteria:
    - can the part be made with the process?

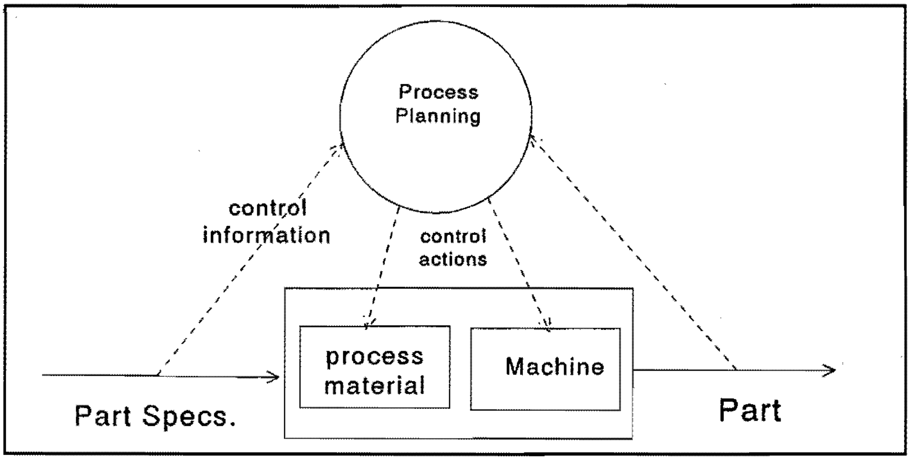


Figure 6. Process planning as a control task (schematically).

- how much effort will it take to do the process planning for the part?
- how well will the process perform in production (product quality, product speed etc.)

2. economical criteria:
   - how much will the process planning (incl. tool-making) cost?
   - how large will the total production volume for the part be?
   - how high will the production costs be?
3. logistical criteria:
   - how much time will process planning take?
   - will the process enable us to react to customer demand?

Because the scores on most of the criteria depend on the effort for the technical process planning task, it is necessary to analyze the consequences of this choice for process planning in more detail.

If the manufacturing processes are given, one can conclude that the process planner has to match process/material variables and manufacturing resources with their variables so that the objective of the specified part in the desired quality and quantity is realized. The determination of process variables values is mainly a technical problem (the process has been chosen). The choice of manufacturing resources has strong logistical and economical consequences. The choice of a certain machine together with the delivery schedule of the part imply the allocation of a part of the capacity of that machine (see section 2). If this capacity is not abundant, process planning is directly linked to production scheduling and the choice of the machine has an important effect on production costs.
For process planning this means that (see: Ashby, 1958):

1- it has to have a specification of the manufacturing process output and it's economical and logistical conditions,
2- it has to have an input-output model of the manufacturing process and the set of manufacturing resources available,
3- it has to define the input-output relations of the manufacturing process and of the available set of manufacturing resources,
4- it has to have sufficient control variety to realize the part within the conditions given.

As sketched in 5.1.1, condition 1 is given by the engineering drawing of the part, the order data and cost goal. To be able to check completeness of the part specifications, a general part model would be needed. Condition 2, refers to a general framework for modelling manufacturing processes and a general framework for modelling manufacturing resources (capacity). A closer consideration of available (general) manufacturing process models should help in finding such a general framework. Production control concepts should be explored for finding a framework for modelling resource. Assuming that general frameworks can be found, condition 3 means that these frameworks have to be operationalized for specific processes and production departments. This operationalization is chosen when the manufacturing process and the production control concept is chosen. For processes, this also touches on the build-up of experience: by storing and systematically analyzing the input and output data for every part these data can help to build a model for a specific process. The data for building such a specific model can either be used directly for similar parts (repetition) or indirectly for input-output functions. The concept 'control variety' in condition 4 means that the set of process variables and the available capacity is large enough to enable the process planner to realize all the specifications of the part to be made.

7. Conclusion

Based on the observations above the following conclusions can be drawn. First, in view of the objective of this thesis, the design/development activities are a more versatile research subject than the production activities. There has been less research on the integration of design development and the importance of design/development for the ability of a company to cope with the competitive criteria seems larger. Second, in terms of contribution to product cost and development time, process planning is an important design/development activity. It can be expected that the manufacturing processes that are planned for influence the IE & MS aspects of process planning more strongly than the resources. The importance of this grows as more alternative processes become available through technological development (see: Van Luttervelt, 1991). Third, the automation of process planning has clearly indicated that process planning is to be seen as the mapping of design information (part specification) on manufacturing processes (and material), the determination of process variable values and the matching of the appropriate process variables values with manufacturing resources (machines).

The above observations lead to the following questions that should be answered in this research project:

1. How are the appropriate knowledge, skills and training for process planners related to the part, the manufacturing processes and resources that the process planner is planning for?

2. How does the appropriate control and organization of process planning depend on the manufacturing process resources and part that is planned and on the manufacturing resources available?

3. Do the possibilities to automate process planning depend on the part and process that is planned for or on the resources that are available?

4. Which freedom of choice should be left to process planning to adapt the part specification to the machines and processes in manufacturing?

It can be stated that the choice of a manufacturing process for making a part has a larger potential impact on the time and costs for process planning than the choice of manufacturing resources (machines). In other words, the combined effect of the complexity of the part and the characteristics of the manufacturing process on the process planning tasks is assumed to be generally larger that the effect of the part and the manufacturing resource chosen. For this reason the translation of parts to manufacturing process variables and the influence of this translation on IE & MS aspects of process planning will now be treated first. In chapter six the effect of the choice of manufacturing resources will be worked out.

CHAPTER 3.

An Industrial Engineering and Management Science view of the manufacturing function: some concepts and definitions

The objective of this chapter is to present two specific IE & MS concepts to be used in the observations of technique in manufacturing. Some definitions of Manufacturing Technology (see Chapter 1) are found to be useful for IE & MS observations. Nevertheless, new concepts are found to be needed. These new concepts reflect the typical Industrial Engineering and Management Science view of technique in manufacturing. As shown in chapter 1, IE & MS observes the technical means as an integrated part of a wider goal-oriented human-means system. Moreover, the total system is observed in terms of a control system. The focal point of the Industrial Engineering and Management Science view is the consequence of certain technical means in manufacturing for the integration of the design/development activities and the production activities in view of the desired costs, timeliness and quality of the products to be made. This asks for some specific concepts.

In section one the usefulness, for IE & MS purposes, of the MT definitions (given in chapter 1) is discussed. Sections two and three present two new concepts specific for Industrial Engineering and Management Science: the manufacturing route and the conceptual description of a part. Examples of these concepts are given. In section four some conclusions are drawn.

1. An Industrial Engineering and Management Science view of manufacturing technique: the need for some new concepts

As derived in the preceding chapter, the subject of this thesis is the influence of manufacturing technique on IE & MS aspects of process planning in companies producing in small batch sizes. It seems necessary to consider whether manufacturing technique has been appropriately defined for that purpose. In chapter one manufacturing technique was defined in a hierarchy of material, manufacturing process and machine (or manufacturing resource). In the case of the traditional black-smith applying a hammer (tool) to forge a piece of metal (material) there is no machine. The movement of, and the energy for, the tool are all supplied by man. The same goes for the integrating activities and for the design/development activities. The integration between the forging operations and other operations on a workpiece will take place in the head of the craftsman. The black-smith will e.g. determine how, and how long, to cool the workpiece before a next operation based on experience. The design and process planning will also take place in the head of the man. A sketch, an example or memory will be translated into a product and how to make it. The (technical) contents of these design/development activities, however, remain a purely technical subject. So, in this example, the Industrial Engineering and Management Science research area starts at the 'machine' level (the machine is a human being) for the production activities and at the first integration level for the design/development activities (because the machine is a human being who can be observed with the material and the sketch of the product as an integrated system).

The product forged by the black-smith (or a practically similar product) can also be made in a highly automated factory. The alternative is technically equal for IE & MS. For IE & MS the differences between the two possibilities are in cost, delivery-time, organization, skills, flexibility etc. This throws up the question whether the definitions given in chapter two is directly applicable in an IE & MS dissertation on the relation between manufacturing means and the IE & MS aspects of process planning.

To solve this problem it seems necessary to take into account the second element of IE & MS research: satisfaction of environmental demands. As shown in chapter two, Mechanical Technology (MT) defines materials, manufacturing processes and machines in terms of what they are, how they work. In IE & MS terms, however, this is not the focal point. How processes work, or what materials are, is irrelevant as long as they satisfy the same market/environmental demands. As stated in chapter one, the satisfaction of customer demand has to be achieved both in qualitative and a quantitative respect. So, IE & MS should define a part and manufacturing means so as to express this indifference for the physical realization of part, process and resource as long as they satisfy customer demand. In the next section these definitions of parts and the manufacturing means will be developed.

2. An Industrial Engineering and Management Science concept: the conceptual description

In the rough sketch of the design process given in chapter one, it was pointed out that the design process starts with a customer demand. Such a demand will usually be in qualitative and vague terms. Before this demand can be translated into engineering terms, which are defined in technical (measurable) entities like weight, speed etc., a more precise description is needed. This description is the product function and it's sub-functions. The translation of function into engineering terms is usually an iterative process between function levels and engineering solutions for these functions (see e.g. Suh, 1990). In the concurrent engineering approach as presented by Clausing and Pugh (1991) at each functional level the engineering solutions are frozen by choosing a design concept.

However, despite the different efforts to define and structure the design process it should remain clear that, from the customer's point-of-view, products are identical when they fulfill the same need. Especially in a discipline like IE & MS it is essential to realize that the market and environmental demands need to be satisfied, not any company standards. For a dissertation on manufacturing technique this is important too since, also on part level, not the part as such but it's role in satisfying customer demand is the objective. A more restricted formulation is that parts are the same when they have the same (sub..sub..)function.

For parts, however, this equal function is not the only criterion. Since parts belong to a subassembly or to a final product they have to 'fit into' this subassembly or final product. This leads to requirements regarding physical aspects of the part. Moreover the part will also have to satisfy some environmental requirements like e.g. safety standards. What these requirements exactly are will differ from situation to situation. The requirements can relate to the size of the part, it's surface roughness etc. This means that, per

situation, the description of a part or subassembly can be broken down in mandatory characteristics and characteristics that are more or less 'free'. Of course, these characteristics are not completely free but they can be varied within certain limits. This variation freedom for example gives the opportunity to the process planner to optimally adapt the part design to the processes with which it should be made. So, for our purposes, a list of mandatory physical and mandatory functional and environmental aspects fully describes a part. The mandatory physical aspects stem from the fact that a part has to fit into a containing sub-assembly or product. The mandatory functional/safety aspects stem from the function that a part has to fulfill in it's containing sub-assembly or product and are only specified physically by means of limits.
In the QFD (see chapter one) scheme that Akao presents (1990: 16-17) quality characteristics of the product (QCP) are translated into QC's for units and parts. The latter translation also includes the determination of the function, the quality standards and the safety standards for each part. Once these have been determined a QFD phase comparable to process planning starts.

This full description in mandatory functional, safety and physical aspects will be called the conceptual description of a part. All physical realizations of a part that satisfy the conceptual description are to be seen as equal from an IE & MS point of view. The choice for a certain alternative can be made on basis of costs, quality and delivery criteria.

The same reasoning goes for the manufacturing input: the semi-finished goods. Mostly, there will not be many physical requirements that a semi-finished good has to satisfy. The functional requirements will often be of overriding importance. However, this does not alter the fact that the idea of the conceptual description is of use too.

Example

Kalpakjian (1987: 1189) gives an interesting example of three realizations of a wing section for an aircraft (see figure 1).

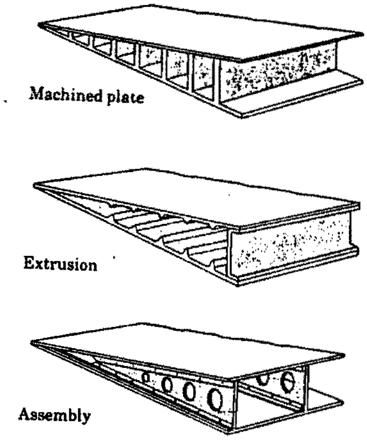
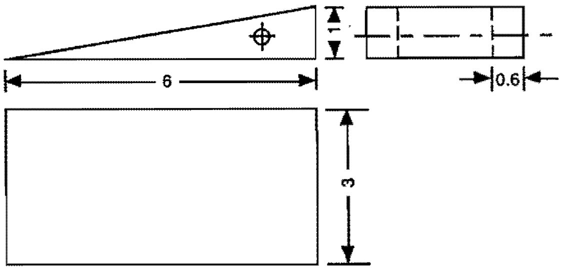


Figure 1. Three realizations of a wing section (from: Kalpakjian, 1987).

Depending on the manufacturing process chosen for making this section, the precise design of the part is different. Even stronger, depending on the process chosen one should speak of a subsystem or of a part. A possible conceptual description of this part is given in figure 2. As shown, some mandatory physical requirements are given. These requirements concern the interfaces of the part with the rest of the product. The mandatory functional requirements are surface quality, strength. The double version of the pivots is a safety requirement.



The conceptual description for a wing-flap section; includes functional requirements:
load
corrosion resistance
surface roughness;
also, interface requirements, as exemplified by the pivot point that joins the flap to the wing.

Figure 2. the conceptual description of the wing section.

3. An Industrial Engineering and Management Science concept: the manufacturing route

In practice, more than one manufacturing process will (almost) always be needed to make a part, which satisfies the conceptual description, out of a semi-finished good. Rarely, a manufacturing process does not require some preparatory process or at least a finishing process. For comparing alternative (series of) manufacturing processes in IE & MS an identical reasoning as for the conceptual description of a part can be followed. The output of the processes should satisfy the same conceptual part description and environmental demands. However, to have comparable entities, not only the output of the processes has to be identical but the input has to be comparable as well. The inputs to alternative (series of) manufacturing process generally are not identical since they are a function of the part to be made and the manufacturing process and the machine chosen and thus do not only depend on customer demand. So, a manufacturing process that only finishes a semi-finished good that was pre-processed can not be compared to a manufacturing process that forms and finishes raw stock. Consequently, only if alternative (series of) processes result in a part that satisfies the same conceptual description and if these processes start from a standard semi-finished good, these series of processes can be compared from an IE & MS point-of-view[1].

From this it can be concluded that instead of single manufacturing processes, sets of processes which result in an equal part (defined above), and which start from standard semi-finished goods should be compared. These sets of processes will be called manufacturing routes.

Example

Breun and Wohnig (1990) present three methods to make a drawing tool (which is the product here) consisting of three elements and having one set of functional requirements. All methods consist of several steps from the standard semi-finished good up to the finished tool (see figure 3). The sets of steps presented here are the different manufacturing routes for making the product.

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[1] This could lead to a discussion of what is a standard semi-finished good but this discussion is not elaborated any further here. For practical reasons a standard semi-finished good is defined here as a semi-finished good that can be bought on the market from a third party.

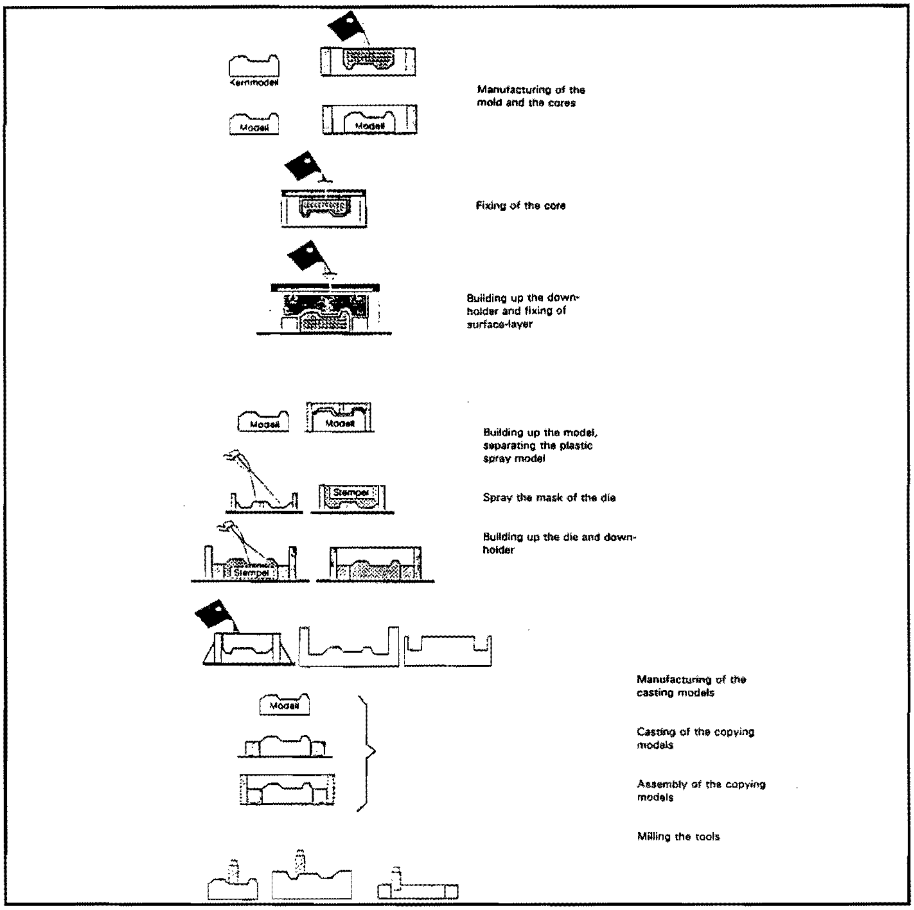


Figure 3. Three manufacturing routes (from: Breun & Wohnig, 1991).

4. Conclusion

The two concepts (manufacturing route and conceptual description) presented in this chapter are important for the study of process planning for manufacturing. The concepts focus attention on the function that process planning has in the design/development activities. This function is the translation of customer demands and of higher level product design decisions into a set of manufacturing instructions, means and aids that satisfies these requirements for least costs and in the demanded delivery terms. The alternative sets should be really comparable that is all processes involved should be taken into account.

CHAPTER 4.

The influence of manufacturing processes on IE & MS aspects of process planning: task uncertainty as linking variable.

In chapter 2 it was concluded that in the literature the influence of 'technology' (which usually has the meaning of technique in our context), on IE & MS aspects of different functions in a company, has been investigated mainly for the manufacturing activities and their control.

A second conclusion was that the design and development activities are considered to be of increasing importance for the competitive success of manufacturing companies. Process planning was chosen as the concrete development activity for investigation. This choice was justified by pointing at the relevance, in managerial terms, of process planning.

Manufacturing processes are thought to have a larger potential impact on IE & MS aspects of process planning than manufacturing resources (see Chapter 2). In this chapter, therefore, a framework for understanding the influence of manufacturing processes on the IE & MS aspects of process planning is worked out.

It should be stressed that the reasoning presented below refers to one process step (of a manufacturing route). If more processing steps are needed to manufacture a part, the reasoning presented here can be applied to the each of the individual steps, taking into account the interaction between the different steps.

In section 1 task uncertainty is presented as linking concept between technology and IE & MS aspects of tasks that are related to this technology. Section 2 presents a further definition of manufacturing processes and of parts. The sections 3, 4 and 5 relate the characteristics of manufacturing processes and of parts to the task uncertainty in process planning. Section 6 treats the influence on process planning task uncertainty of process variables unknown to the process planner. Based on these observations, a research hypothesis is formulated in section 7.

1. Task uncertainty as a linking concept between technique and IE & MS aspects of tasks

As said, from an IE & MS perspective manufacturing processes as such are not very interesting. For process planning this means that we are interested in the influence of manufacturing processes on the tools, the (human) skills, the organization and control that are best suited for carrying out the process planning tasks for a specific process.

In the literature the influence of technology on the aspects mentioned above has been investigated on task-level and on organizational level (for an overview see e.g.: Gerwin, 1981). In view of the research interests sketched, the literature on the influence of 'technology' on task-level is important here. The two constructs that seem to determine this influence are:

- interconnectedness or interdependence of tasks,
- task uncertainty or (reciprocal) task routineness.

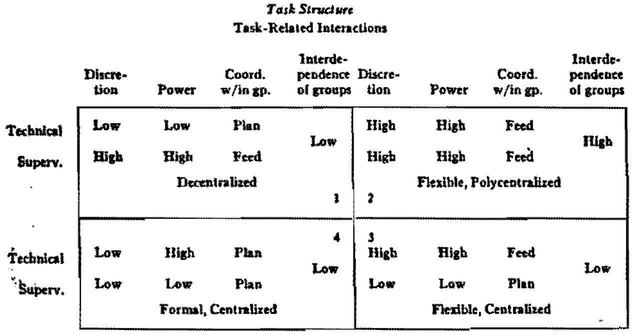
As stated in chapter two, Galbraith (1973) defines task uncertainty as the difference between the amount of information needed for a task and the amount of information available for a task. Van de Ven et al. (1976) define interconnectedness in terms of work flow patterns and in terms of 'the extent to which unit members discuss how to perform each task in order to do the work in the unit'. The interconnectedness construct thus seems to refer to the split up of work over different operators or employees on the one hand and the extent to which each of them can carry out his/her task independently on the other hand. As will become clear later (chapter 5) such aspects are also included in measures for task uncertainty. Therefore, in this research the concept of task uncertainty will have a central role in linking manufacturing technique to managerial aspects of process planning.

Perrow (1967) defines technology as (1967: 195-196) 'the actions that an individual performs upon an object, with or without the aid of tools or mechanic devices, in order to make some change in that object'. In Perrow's reasoning, these objects can be human beings as well as stones, iron etc. He states that two aspects of technology vary independently:

- the number of exceptions that must be handled,
- the degree to which search (in case of an exception) is an analyzable procedure.

If a technology is high on the first aspect and low on the second, Perrow calls this technology 'non-routine'(square 2 in figure 1). The opposite is called 'routine' (square 4 in figure 1). The other combinations are called 'craft' (low, low) (square 1 in figure 1) and 'engineering' (high, high) (square 3 in figure 1)

respectively. Perrow hypothesizes task structure to vary with these characteristics of technology. As the elements of task structure Perrow discerns:
= discretion: judgements about whether close supervision is required (about changing programs etc.),
= power: influence on basic goals or strategies,
= coordination: mechanisms for tuning actions,
= interdependence of groups: degree to which a working group can determine it's own working conditions.
Figure 4.1 shows the hypothesized score of the four technologies on these aspects.



Task Structure
Task-Related Interactions

	Discretion	Power	Coord. w/in gp.	Interdependence of groups	Discretion	Power	Coord. w/in gp.	Interdependence of groups
Technical	Low	Low	Plan	Low	High	High	Feed	High
Superv.	High	High	Feed		High	High	Feed	
		Decentralized		1	2	Flexible, Polycentralized		
				4	3			
Technical	Low	High	Plan	Low	High	High	Feed	Low
Superv.	Low	Low	Plan		Low	Low	Plan	
		Formal, Centralized				Flexible, Centralized		

Figure 4.1. Task uncertainty and it's consequences (from: Perrow, 1967).

This figure makes clear that, according to Perrow, task uncertainty influences such managerial task aspects as the skills that are asked of an individual worker, the cooperation of workers and the way in which the jobs of workers should be organized and supervised in order to achieve the highest organizational performance.

Among the few prominent empirical research results on technical influence on task-level are Hage & Aiken (1969) and Van de Ven et al. (1976). Following Perrow, Hage & Aiken operationalize technology as 'the routineness of tasks' and find significant positive relationships with the presence of (and the specificity of) job descriptions and manuals. Van de Ven et al. use task uncertainty as a measure for technology and find significant negative relations with formalized coordination modes among jobs (compare to Perrow's score of interdependence of groups in figure 1).

Galbraith (1973) also sees 'task uncertainty' as the main determinant of organization design. He states that increasing uncertainty leads to increasing information processing demand. At a certain point, this information processing demand can no longer be handled by the specific organizational unit. Then, organizational measures are needed to increase the information processing capacity of the unit or reduce the information processing demand. The organizational measures can be one of the following four (also given in chapter 2):

- creation of slack resources,
- creation of self-contained tasks,
- investment in vertical information systems,
- creation of lateral relations.

So, according to Galbraith, management should cope with the effect of task uncertainty by adapting the organization structure, the control structure or the information systems in the organization.

Reimann (1980) distinguishes between work-flow and system level perspectives of the technology-structure relation. He concludes that (1980: 76): 'the results of this study have added some additional evidence to that of a number of earlier studies in support of a theory that connects organization structure to technology via the organization's need to control the activities of its members and subunits. In addition, the research results have reinforced the theoretical notion that technology will influence structure primarily at that organizational level at which it has the most direct impact in its requirements for coordination and control.' This conclusion supports our expectation that manufacturing processes will influence the organization structure of process planning.

This overview of the literature shows that the task uncertainty has some clear relations to IE & MS aspects of a task. For optimal functioning of an organizational unit, the organization of tasks, the information systems that support workers in carrying out a task, the coordination and control of tasks and the skills and training required for carrying out a task should all be tuned to the task uncertainty experienced. This means that an existing organizational unit, for optimal functioning, should either adapt itself on these aspects or that it should reduce the uncertainty experienced. In short, task uncertainty seems a very useful concept to link manufacturing technique (or for many authors: technology) to IE & MS aspects of process planning.

2. The choice of a manufacturing process model and a part model

2.1. A model of manufacturing processes

Given that the translation of part characteristics to manufacturing process variable values was chosen as research subject, a more detailed description of parts and manufacturing processes is needed. Therefore, a model of manufacturing processes should be found which gives the variables with which a manufacturing process can be specified. The same goes for parts.
From a review of the relevant literature in Manufacturing Technology (MT) and related disciplines the following can be concluded.
A division can be made in three types of descriptions of manufacturing processes. First, process descriptions or models which are based on the way in which manufacturing processes work. DIN8580 (1985) e.g. divides manufacturing processes in groups like: 'forming', 'cutting', etc. These groups are further divided in e.g. 'cutting with a rotating blade' and 'cutting with a translating blade'. Other examples of such descriptions are: Hubka (1984), Hofner (1969), Kienzle (1963). This group of descriptions learns that the manufacturing processes discussed here all are transformations of objects by means of energy. So, it is necessary to have an object to be transformed and to apply energy to that object. Since such processes always have an energy efficiency below 100%, it is also necessary to carry off excess energy,
Second, descriptions that use the inputs and outputs of manufacturing operations as their basis. Alting (1982) sees manufacturing processes as processes that transform objects, energy and information into products and waste.
Comparable descriptions are given by Wolffgram (1978), Lange (1985), Schey (1987) and Eversheim et al. (1991).
Third, descriptions which are a mix of the categories above, eg. Kudo (1980).

As stated earlier, from an IE & MS point of view, manufacturing processes are means to make products. In other words, the objective of production is to make products and not to have manufacturing processes: manufacturing processes in themselves are, strictly speaking, irrelevant. Consequently, we are interested in the restrictions that these processes put on producing products in the sequence, in the time-span and for the expenditures that are considered as acceptable. So, from an IE & MS point of view, the input/output models are most interesting.

A closer study of input/output models reveals that Lange (1988) gives one of the most extensive and systematic models. His model consists of eight aspects:

1- characteristics of the material/object,
2- the deformation zone: the behavior of the material/object while it is being transformed,
3- the contactzone between material/object and tool,
4- characteristics of the material/object to be transformed,
5- reactions of the product with it's physical environment,
6- the tools,
7- the machine,
8- the production environment of the machine.

According to Lange, the first six aspects are universal for forming processes and can be filled in with data of any other forming process (see figure 2).

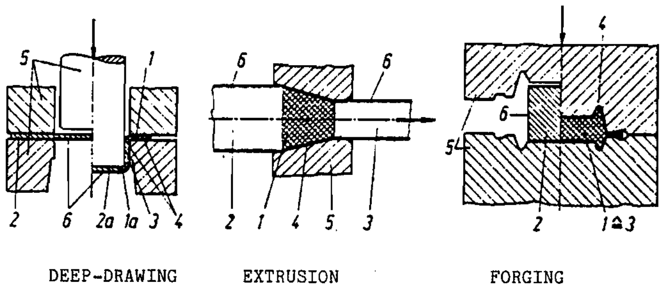


Figure 2. Lange's model schematically (from: Lange, 1988).

For the purposes of this research, it is desirable to have a more general model i.e. not only for forming processes. So, here a manufacturing process is described by specifying:

- the object to be transformed (compare to 4-),
- the tools and fixtures (compare to 6-),
- the relative movement of tools and object (compare to 2- and 3-),

- the energy applied (compare to 2- and 3-),
- the auxiliary materials used (compare to 3-).

Such a description represents the variables of manufacturing processes as given by the more specific model of Lange (and a.o. Alting (1982)) and as far as they have to be specified by process planning. In this specification the behavior of the part after processing (see the Lange model) and the carrying off of excess energy (see above) have to be taken into account as boundary conditions.

2.2. A model of parts

As concluded in chapter two, the control task of process planning also asks for a part model. According to Baumann (1982), a part is fully described physically by giving a description of the part's characteristics:

- shape,
- material,
- tolerances,
- surface roughness,
- dimensions.

The part shape can be described as a whole or in terms of form features. The other part characteristics can be described in the standard measures. Internal aspects of a part (e.g. inclusions) are not taken into regard here. For some manufacturing processes this means a crude oversimplification. The approach taken however does not principally exclude these aspects. The description is also explicitly meant for parts not for subassemblies or products.

As shown in chapter 3, the conceptual description of a part is the relevant criterion for IE & MS, not the exact physical description. In the process-planning for a specific manufacturing process, however, the part has to be fully specified. So, when manufacturing processes are compared, the part, in it's exact specification, can differ from process to process. As was shown, this is acceptable as long as the part satisfies the conceptual description.

3. Task uncertainty in process planning and the build-up of a manufacturing process input-output model

As presented above, Galbraith (1973) defines task uncertainty as the difference between the amount of information needed and the amount of information available for a task. According to this author, the amount of information needed for a task depends on:

- the diversity of outputs of the task,
- the number of different input resources to perform the task,
- the level of goal difficulty.

As shown, the inputs at the start of the process planning of a part generally consist of the engineering drawings of single parts and of their assembly, the bill of materials for assembly and manufacturing and the order data. Here, the number of the design inputs of the task is assumed constant per part. The diversity of outputs for one specific manufacturing process is assumed to be comparable for each part too. The assumption of equal levels of goal difficulty was already made before.

Under these assumptions, the experience/knowledge of the process planner (which can also be in the form of a process planning data base), and the match of that experience with the information needed to plan a part, determines process planning task uncertainty. Generally speaking, the match between process planning knowledge and necessary information will be close under one of the following two conditions. First, if the part represents a (partial) repetition of a part that has been planned earlier. Then, the processing knowledge of the earlier part can be applied. This can be done on the level of the part as a whole or on the level of (known) part features.

Second, if the knowledge demanded to plan the part can be derived 'easily' from the experience with parts that have been planned earlier. This is the case when the experience with earlier parts has led to process rules that can be applied to the part under consideration.

The above analysis now leads to two research questions:

- which manufacturing processes allow for a high degree of repetitive work in process planning?
- for which manufacturing processes is the formulation of the input-output relations of the manufacturing process difficult?

The former question refers to the comparability between parts. This means either the use of existing parts or design on the basis of existing parts. It seems that the latter approach has both a weak and a strong form. The weak form is variant process planning in which on basis of several criteria parts are defined as comparable. The 'comparable' process plans are used as a reference to determine new process plans. The strong form is the use of features in process planning: a part is broken down into elements for which process planning has a manufacturing solution. However, as Hummel & Brown (1989) point out, the break-down of a part in features will generally be different for different manufacturing processes. Moreover, as a rule, the features used by design will not be directly applicable in manufacturing. Still, Hummel & Brown conclude that (1989: 1): 'features are integral to the automation of experience based reasoning in design and manufacturing'. So, in the light of the goals of this research the influence of a manufacturing process on the applicability of feature based process planning is of interest.

The latter question, above, can also be answered by asking under what conditions this formulation can be conceived as easy. In other words: under what conditions can the structure and the parameters of the input-output relations be formalized directly? These relations can be formalized directly if (see also Georgescu-Roegen, 1971):

1- the part characteristics can be measured exactly,
2- the manufacturing process variables can be measured exactly,
3- the manufacturing process variables are not interdependent,
4- the part characteristics and the manufacturing process variables are related one-to-one,
5- the part characteristics and the manufacturing process variables share the same dimensions,
6- the relation between the part characteristics and the manufacturing process variables is identical for the whole domain of each part characteristic.

Under these conditions, the structure and the parameters of the relations can be formalized directly since these conditions mean that the relations consist of a set of mathematical functions that relate process variables and part characteristics one-to-one. In reality, however, several of these conditions will not hold. Not fulfilling the conditions 4, 5 and 6 will make it more difficult to find the parameters and the structure of the relations. Several relations between independent variable(s) and a dependent variable have to be found in this situation. With existing statistical techniques it is still possible to find the structure and parameters of the input-output relations (assuming enough data are available). Releasing the conditions 1, 2 and 3 will have more critical consequences. Condition 3 will now be discussed first. Then conditions 1 and 2 are treated.

4. The influence of the interdependence of manufacturing process variables

The interdependence idea (condition 3) can be modeled in a process matrix B:

$$\{PC\} = [B] \cdot \{PV\}.$$

B relates the part characteristics (PC) (given) to the manufacturing process variables (PV) (to be determined). If in such a matrix there are values unequal to zero (meaning there is a relation) only on the diagonal of the matrix, the process variables are independent: they can be determined one by one. If values unequal to zero are on the diagonal and either above or under the diagonal (figure 3), there is interdependence but a sequential determination of the process variables is possible.

$$\begin{pmatrix} X & X & X \\ 0 & X & X \\ 0 & 0 & X \end{pmatrix}$$

Figure 3. Process Matrix.

In cases of values unequal to zero above and under the diagonal, or in case of non-square matrix, real interdependence exists (figure 4). The process variables influence each other mutually and the fixing of the value of one of the variables can not be done without taken the others into account.

$$\begin{pmatrix} X & 0 & 0 & 0 & X \\ X & X & 0 & X & X \\ X & X & X & 0 & X \\ 0 & 0 & X & X & 0 \end{pmatrix}$$

Figure 4. Non-square Process Matrix.

The ideas seem to run parallel to those presented by Suh (1990) on product-(part-)design. He presents the idea of the design matrix 'A':

$$\{FR\} = [A] \, . \, \{DP\}$$

Here the matrix A relates Functional Requirements (specified in the vector {FR}) to Design Parameters (in our terms: part characteristics: {PC} instead of {DP}). Suh states that a product should be designed such that each part characteristic corresponds with one function.

The above argument learns that the interdependence of manufacturing process variables influences the matching between process planning knowledge and the knowledge needed for planning a specific part. Both the repetition of elements of a part in process planning and the linking of process variables values for different parts become more difficult if the elements of parts a related to each other. In deep drawing for example the shape of the blank and the punch load are interdependent and the determination of these variables generally is a specialists' task.

5. The influence of the measurability of part characteristics and of manufacturing process variables

Equally critical as the interdependence of process variables seems the release of conditions 1 and 2. If these conditions are fully satisfied the process variables and the part characteristics can be measured on ratio- or interval-scales. Then, the measurement of the characteristics and variables is a straightforward operation. Finding the parameters and structure of matrix B seems much more difficult, if not impossible, if the process variables and part characteristics can only be measured on a nominal- or ordinal-scale and have an infinite variation (see also: Georgescu-Roegen, 1971). In that situation one can only say that the values of these part characteristics and process variables differ from each other but not how much. Three-dimensional irregular shapes, for example, are a characteristic of this type. If such a part characteristic has to be translated into a process variable of the same type (for example the shape of a tool) this is not necessarily problematic: directly copying the shapes is possible then. However, in deep drawing the relation between three dimensional irregular shapes and a.o. the amount of grease needed can hardly be formalized. This task is generally carried out by experienced operators. Other factors can influence the measurement scale too.

First, the scale of measuring variables and characteristics can of course be influenced by the measuring devices available. An example is the measurement of surface roughness. This can be measured by visual inspection, contact gages and capacitance-based sensors (Noaker, 1991). The first method will result in a nominal scale characteristic, the latter two methods result in an interval-scale characteristic (though with different accuracy).

Second, the values of the variables will also depend on company specific aspects such as expected total number of products to be made. For several manufacturing processes the quality of the tools (e.g. the material) can be chosen depending on the desired tool-life.

The analysis of the factors that contribute to the difficulty of formalizing the input-output relations also gives an idea of the influence of manufacturing processes on the applicability of features in process planning. The feature-based approach makes it possible to break down nominal continuous variables (like part shape) into sub-variables (e.g. shape elements) that can be repeated. On the level of these sub-variables a sort of variant process planning can be used: the elements are related to earlier made elements for which a manufacturing solution is known. An important assumption in feature-based process planning however is that features can be isolated and that a set of manufacturing process variables can be allocated to that specific feature. In case of interdependence between the manufacturing process variables this is not possible. An example is the manufacturing of a solid part by machining it out of a blank or by casting it. When the part is machined the process planner can, in principal, specify for each slot, pocket, notch etc. separately how (i.e. with which values of the manufacturing process variables) it is made. When the part is cast the same features have a different meaning or even do not have a meaning at all. In the case of casting namely, all slots, pockets, notches etc. together determine most of the values of the manufacturing process variables. The interactions are difficult to operationalize. So, it is difficult, if not impossible, to link these features individually to manufacturing process variable values for casting. But even in machining total independence, or predicted dependence, of the features does not always exist. Intersecting features e.g. can lead to interdependence of process variables.

Another important assumption in feature based process planning is that the part can indeed be broken down completely in terms of predefined features. Although a base of atomic features and (user-defined) features is sufficient to cover most parts it will not cover every possible part.

Concludingly, we can say that the influence of the manufacturing process on the degree to which the process planning tasks are repetitive works through the interdependence of process variables. If many of the process variables of a certain manufacturing process are interdependent, it is difficult to break down a part in separate features and to derive the process variable values from the individual features.

6. The effect of unknown manufacturing process variables

An important assumption in sections 4 and 5 is that all relevant process variables are known to the process planner. This, however, might not always be true. In the context of this research project it seems important to be able to account for the possible neglect of certain variables.

It is assumed that all variables in the adapted Lange model are specified in process planning. It is possible, however, that a variable is not specified at the highest possible measurement scale. This means that process planning specifies a variable but that in reality an aspect of that variable is the relevant variable.

An example could be that process planning specifies a certain material (steel for a rubber cushion deep drawing die) but that in reality the material hardness is the relevant variable (so that a wooden tool is possible too).

Two questions seem to be of importance:

- is it likely that the relevant variable exceeds a process tolerance?
- how does the relevant variable behave over time?

The following situations seem to be possible;

1. The relevant variable always has the same value which lies within the specified value.

   example: a color is specified, but a radiation with a certain wavelength is the relevant variable. This will not lead to problems as long as the definition of color is broad enough to capture the relevant wavelength.

2. The relevant variable varies stochastically and 'sometimes' exceeds the process tolerance.

   example: A material is specified but the elasticity is the relevant variable. Elasticity varies stochastically through a material. If process planning by chance tested material with the right elasticity such a wrong specification will lead to a unexpectedly high scrap rates in production.

3. The relevant variable varies as a function of other factors.

   a. The relevant variable changes steadily and, after a while, exceeds the tolerance.

   example: tool wear that changes the tool shape from the desired shape

   b. The relevant variable changes now and then.

   example: (without knowing) blanks are sometimes cut in the roll direction, sometimes not. Dependent on this orientation of the blank material the characteristics of the material change. Or, as an example of less controllable influences: weather (humidity, temperature) changes.

The possibilities are summarized in figure 5.

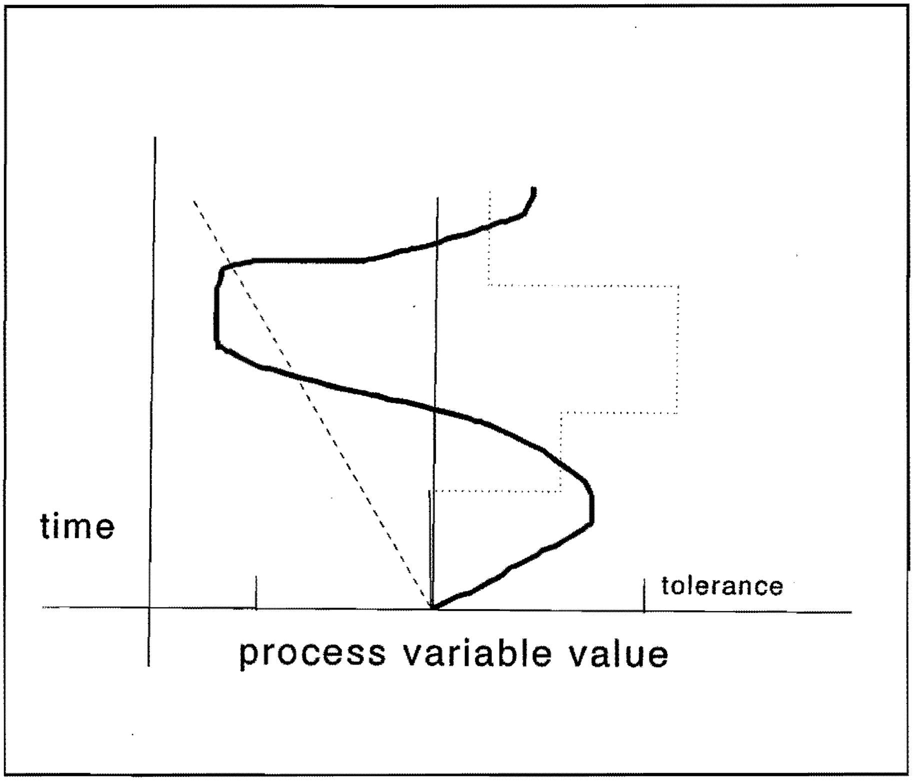


Figure 5. Different patterns of unknown variables.

It is important to take into account that the situations sketched can play a role in the specification of the process variables. This can be done as follows;
- 2.: by comparing the scrap-rates specified in advance by process planning with the actual scrap-rates.
- 3.b.: by scanning the pattern of the scrap-rates for a certain process for 'sudden' peaks and troughs.

The other situations (1 and 3a.) are more difficult to cope with:
- 1.: an unknown and hidden variable can not easily be tracked. Only extra technical knowledge can help here.
- 3.a.: the prevention of the effect of such variables generally is not a process planning task. Quality assurance should feed-back to process planning though.

In short, to take account of the effect of the unknown variables the following questions should be added to a questionnaire for investigation of a process matrix:

- what was the scrap-rate specified by process planning and what is the actual scrap-rate?
- do high scrap-rates suddenly occur and vanish?

7. Conclusions & Research Hypothesis

It can be concluded that task uncertainty is a concept that can be used to link manufacturing technique to IE & MS aspects of a task or of the organizational unit in which the task is carried out. It is assumed that the external factors that influence task uncertainty should either be kept at a level that the organization unit, it's members, it's control systems etc. can cope with or the organization, the skills of it's members etc. should be adapted to cope with this task uncertainty.

In this chapter the task uncertainty that stems from the machine choice in process planning is not taken into account. This chapter only observes the uncertainty in the task of determining the manufacturing process variable values from the characteristics of the part that is planned.

It can be argued that, for process planning, task uncertainty is low when process planning has an exact model of the manufacturing process, and of the part that is planned for, at it's disposal. It is difficult to make such an exact model when the process variables are interdependent or when the process variables and part characteristics can not be readily quantified.

Based on the observations above, a hypothesis for empirical research can be formulated. This hypothesis is that the task uncertainty in process planning increases when:

1- more part characteristics and manufacturing process variables, involved in this task:
    a. are to be measured on a nominal scale,
    b. are continuous,
    c. are not repetitions of (elements of) earlier made parts,
2- more manufacturing process variables involved in the task are interdependent.

The measurement scale criterion (1-a. & b.) refers to the measurement scale <u>in the relation</u> between manufacturing process variables and part characteristics. If these variables are to be measured on a nominal scale and if they are continuous one can register from experience that when the values of the part characteristics change, the values of the process variables change as well, but one can not say how much. The other extreme are continuous variables that can be measured on a ratio scale. Between such variables exact mathematical relations can be found.

If this hypothesis could be supported through empirical research this would mean that indeed manufacturing technique has been linked to IE & MS aspects of process planning. Aspects of manufacturing process variables would have been linked to task uncertainty which in turns relates to IE & MS aspects of a task. Referring to Galbraith (1973) we expect poor measurability and interdependence of process variables to go together with either organizational measures like lateral relations and vertical information systems or with long throughputtimes.

To test the hypothesis empirical research was carried out. This was done in industry in small batch manufacturing for mechanical manufacturing processes. The research design and the results are reported in the next chapter.

CHAPTER 5.

The influence of manufacturing processes on task uncertainty in process planning: empirical results

In the foregoing chapter a research hypothesis on the relation between aspects of:

- manufacturing processes,
- parts,

and task uncertainty in process planning was derived from the literature. To investigate this hypothesis, data were gathered in a field experiment in seven companies and for each of the four manufacturing processes studied (milling, die casting, deep-drawing and rubber-cushion deep-drawing). In this chapter, the research design and the analysis of the data will be presented.

In the field experiment two important conditions were satisfied.

First, it was checked that the specific part under investigation can indeed be made with the specific manufacturing process. For this, sometimes a part description has to be adapted in order to be able to make it with a certain manufacturing process. An example of such an adaption of the part's specification can be found in closed-die forging. For this process, parts often have to be produced with a flange in order to make the forging possible. This means that the part specification for process planning is different from the original one.

Second, in the observation on the influence of manufacturing processes on process planning, tool manufacturing is not included since the manufacturing process(es) used to make the tooling are not to be mixed with the manufacturing process the tooling is made for. Tool manufacturing has it's own process planning (based on the tool design) in which an identical influence of the manufacturing process on process planning can be expected as in manufacturing. So, although the result of tool manufacturing is determinant for the manufacturing process, the influence of the processes for tool manufacturing on tool process planning should be separated from the influence of the part manufacturing process on part process planning. Tool design, however, has to

be seen as belonging to process planning for the manufacturing process for making the part. This task is included in the observations in this chapter.
Third, in order to fulfill the condition of similar level of difficulty in the process planning tasks that are to be compared it is assumed that the output of process planning is such that all variables of a manufacturing process (the object to be transformed, the energy to be applied, the carrying off of excess energy) are specified when relevant. For the same reason in the companies under investigation the operating conditions for a certain manufacturing process (speed, accuracy etc.) are comparable.
Fourth, companies in small batch manufacturing with mechanical manufacturing processes were chosen. Process planning here is a function that translates a frequent stream of part specifications into manufacturing instructions.

Section 1 presents the research design used and the operationalizations of the concepts in the hypothesis. In section 2 some data from a comparable earlier investigation are discussed as a reference for the results of the measurements to be presented. In section 3 the results of these measurements are presented. Finally, in section 4 these results are discussed and in section 5 some conclusions are drawn.

1. Research Design, Research Objects and Operationalizations

1.1. Research Scheme

The hypothesis on the relation between part characteristics and manufacturing process variables on the one hand and task uncertainty in process planning on the other hand, presented in chapter 4, is that the task uncertainty[1] in process planning increases when:

- more part characteristics and manufacturing process variables, involved in this task:
  . are to be measured on a nominal scale,
  . are continuous,
  . are not repetitions of (elements of) earlier made parts,

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[1] measured by means of variables as given in the literature (see chapter 4, section 4, and this chapter, section 1.4)

- more manufacturing process variables involved in the task are interdependent.

So, the question to be answered on basis of the research is whether or not the uncertainty in process planning tasks is related to the difficulty of translating part characteristics into process variables (due to their measurement scale and their continuous/discrete character and to the interdependence between process variables. Figure 1 gives the research scheme for this question.

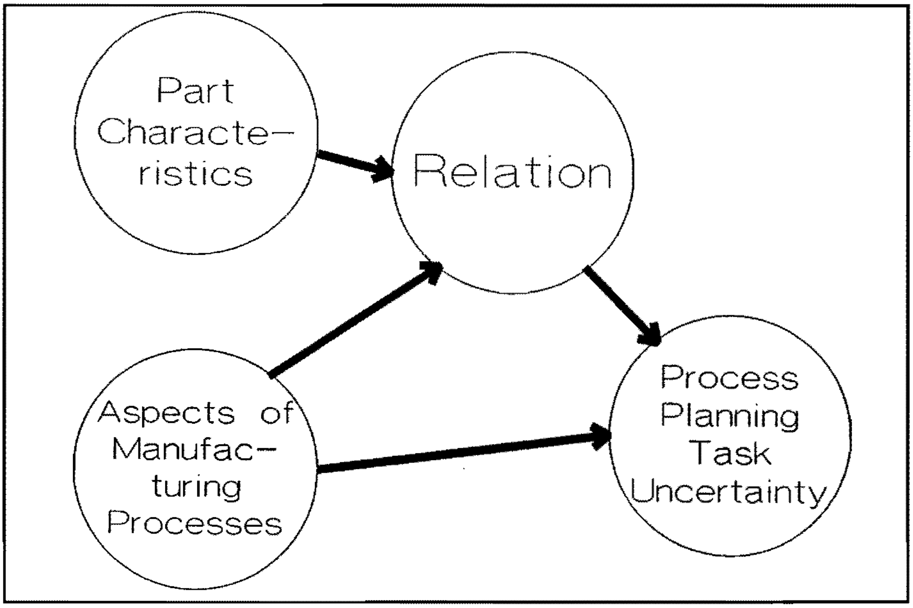

Figure 1. The research scheme.

1.2. Research Objects

On theoretical grounds, the application area of this research was already restricted to manufacturing companies producing parts in small batch-sizes (see chapter 3) and small total production volume per part. The companies that participated in this research are all suppliers of parts, mainly to larger assembly operations. Both independent companies and single plants of larger firms were included. The latter distinction was not considered relevant: the information exchange between the factories and parents were not found to be much different from the information exchange between suppliers and customers.

The manufacturing processes investigated were chosen for the following reason. In Mechanical Engineering a distinction similar to the following one is usually made:
- preforming processes (e.g. casting),
- forming processes (e.g. forging),
- separating processes (e.g. cutting),
- joining processes (e.g. welding),
- surface treating processes (e.g. painting),
- processes changing material characteristics (e.g. heat treatment).

Most technical classifications of processes are based on this distinction (e.g. DIN8580). In universities, the ME faculty is usually split up along these lines. For this reason the four manufacturing processes that were chosen for this research were picked so as to cover three important[2] process groups:
- for separating processes: milling,
- for forming processes: deep drawing (in two versions),
- for preforming processes: die casting.

1.3. Research Design

In the participating companies first the process matrix for the manufacturing process under regard was mapped. This was done through a structured interview with one or two process specialists (experienced process planners or technical staff members). The interview questions were structured along the elements of the manufacturing process model by Lange (see chapter 4). The different elements were detailed beforehand as far as possible with the help of technical literature. In these interviews the character of the process variables (measurement scale, continuous/discrete) was also determined.

Per process planning task, the difficulty of translating part characteristics into process variables was measured as follows. The respondents were asked to select three parts being representative for parts that are respectively easy, average and difficult for process planning. The three parts were scored on their characteristics. Next the respondents were asked to score the uncertainty in the process planning tasks for the particular part. As will be shown, the uncertainty score was established with the help of questions derived from the literature.

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[2] These groups are important because they are assumed to be the main determinants for a part's shape.

1.4. Operationalizations

The operationalization of the variables used is as follows. In each company three parts were studied. Per part, for each task in process-planning, the task uncertainty was scored on 6 uncertainty variables derived from the literature. The product of the score of a part on these task variables was taken as a measure of uncertainty in that process-planning task (UNCERPRO).

The uncertainty variables used in this research were derived from:
- Lynch (1974) who operationalizes Perrow's technology construct,
- Galbraith (1973) who gives the organizational measures to cope with uncertainty,
- Van de Ven, Delbecq & Koenig (1976) and Downey & Slocum (1975) who present task uncertainty measures,
- Hazlehurst (1967) who presents task difficulty measurement scales.

The elements of UNCERPRO are:
- EXPERIEN
  The experience a process-planner needs for this task. This variable was operationalized as a number of years an individual had worked on his or her current job[3].
- STANPROC
  The degree of standardness of the procedures used in this task. This variable was operationalized by the four level scale as presented by Hazlehurst.
- CLEAPROC
  The clearness of the search behavior in this task. This variable was operationalized by the four level scale as presented by Lynch.
- TIME
  The time needed for this task. This variable was operationalized as the hours actually worked on this task by the individual performing the task.
- CONSULT
  Whether or not somebody was consulted in carrying out the task. This variable was operationalized as a boolean variable indicating yes whenever some colleague or outside person was consulted for his or her specialized knowledge needed to fulfil the task.
- REWORK
  Whether or not rework on he results of the task had to be done.

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[3] This is an identical operationalization as used by Early et al. (1990) in an investigation of the moderating effects of experience and task complexity on the result of goal setting. This operationalization stresses the importance of skills developed through direct experience versus skills developed through formal training. Myers & Davids (1992) show that tacit skills are of overriding importance to the performance of individuals in tasks, certainly for complex technical tasks.

> This variable was operationalized as a boolean variable indicating yes whenever (parts of) the task had to be repeated due to flaws in the task output detected by persons carrying out a task that follows the task under regard.

As a process planning task the determination of each of the process variables was taken. Per company it was checked whether the determination of each process variable was indeed a separate task. If not, the determination of two or more process variables, as clustered in a process planning task in that company, was considered as a task.

The part characteristics were scored on:
- the 'highest' possible measurement scale (nominal, ordinal, interval, ratio: 4 to 1),
- whether the characteristic are discrete or continuous (1,2).

These two scores were multiplied thus constructing a high score for nominal ánd continuous characteristics (4 times 2 is 8). The same was done for the relevant process variables per task. The product of the part and process variable scores was taken as a measure for the difficulty of translation of part characteristics into process variables (VERTMOEI). A parallel procedure was followed for the measurement of (the impact of) interdependence of process variables (AfHANK). Whether or not (2,1) the task asked for consideration of the behavior of the part after transformation was also taken into account (BEHAVAFT)[4]. A possible correlation of the uncertainty with the character of the different process planning sub-tasks was investigated in the variable TASKNEW.

2. Reference Data

In order to get some idea as to what kind of results come out of the experiment and to give a basis for comparison of those results, here some reference data are given. Almenraeder (1983) presents the results of an investigation on the factors that determine the time needed for making process plans. According to the author, the making of process plans is one of the short-term tasks of process planning. The other short-term process planning tasks he distinguishes are:
- quotation,
- planning preparation,

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[4] This is an aspect in the Lange model (see chapter 4).

- determination of the bill-of-material,
- NC programming,
- design of specific tools.

Among the medium-term tasks of process planning Almenraeder discerns e.g. quality assurance and cost control. As long-term process planning tasks he counts a.o. methods development and investment planning. Clearly, Almenraeder's choice to investigate only one of the short-term process planning tasks will lead to somewhat different results than in this investigation. Notably, the design of specific tooling is considered very important here (see chapter 2) but is not studied by Almenraeder. This can be understood from the choice of manufacturing processes for his research: turning, milling, grinding and drilling. Most parts these processes do not demand specific manufacturing tooling. It is less obvious why Almenraeder does not include NC programming in his observations. This task is known as being time consuming and error prone, also for the manufacturing processes investigated by Almenraeder.

According to Almenraeder, the sub-tasks of the task 'making process plans' are:

- determination of raw stock,
- determination of the manufacturing route,
- specification of the process variables for each operation,
- machine choice,
- tooling choice,
- processing time calculation.

Together these sub-tasks should lead to a process plan which consists of;

- general data: a.o. an identification number of the process plan itself,
- object dependent data: a.o. part number, material specifications, part name,
- object processing dependent data:
  - . the manufacturing processes,
  - . the manufacturing route,
  - . the operator instructions per operation,
  - . the machine for each operation,
  - . the tools & fixtures for each operation,
  - . the gauges for each operation,
  - . the time standard for each operation.

Almenraeder presents five general variables that influence the time needed for making a process plan:

- environmental influences,
- company specific influences,
- influences of production,

- object dependent influences,
- organizational influences.

The first two categories are not taken into account by this author since these influences are assumed to be 'indirect'. Of the other three, the influence of production is held constant by limiting the research to one-of-a-kind and small series production. This is the same environment as that of the research reported in this thesis. In a field experiment the author then investigates the influence of the object, or in other words the influence of the part characteristics, and the influence of the process planning organization on the time needed for process planning.

Based on their high frequency of occurrence in one-of-a-kind and small series manufacturing, Almenraeder chooses 'rotation symmetric parts without deviations' and the manufacturing processes: turning, milling, grinding and drilling as subjects for his field experiment. Per process, the part characteristics that are assumed to influence the time needed for making a process plan are grouped in three categories (see also table 1 for the complete list):

- geometrical characteristics typical for the process: for milling these are e.g.: number of flat surfaces, number of one dimensionally curved surfaces, number of two dimensionally curved surfaces,
- general geometrical part characteristics: e.g. length and diameter of raw stock, number of dimensions on the drawing,
- technological part characteristics: e.g. number of dimensional tolerances, number of shape tolerances, heat treatment.

The organizational variables taken into account in the investigation are:

- the degree of automation of the aids for process planning: e.g. calculators, PC's, networks,
- the degree of automation of the information carriers: e.g. books, semi-automated systems, computer data bases,
- the qualification of the personnel in process planning: e.g. trained workers, technicians, engineers.

The field experiment was based on 65 parts from 15 companies. The number of parts was limited to 65 by looking at the marginal effect of extra parts on the over-all average planning time and the spread in that average. The time needed for making the process plans was found to range between 11 and 120 minutes. Almenraeder found this total amount of time to be divided over the sub-tasks as follows:

- determination of raw stock: 7.3%
- determination of the manufacturing route: 9.7%
- specification of the process variables and tooling choice: 26.1%

- machine choice: 5.7%
- processing time calculation: 50.4%

The high proportion of time consumed by the processing time calculation is in contrast with the findings in this research project (see following sections). Explanations for this difference can be found in the fact that Almenraeder does not take into account the design of specific tooling and NC programming. For processes that demand specific tooling these tasks consume a lot of time in making a process plan. The qualitative results of the regression analysis of the time spent on making process plans and the independent variables listed above is given in table 1.

Table 1. The relation between the time spent on making process plans and the independent variables (from: Almenraeder, 1983).

	1	2	3	4	5	6	7	8	9	10
determination of raw stock					constant					
determination of the manufacturing route			*	*	*		*			*
specification of the process variables and tooling choice	*	*	*	*			*	*		
machine choice	*	*	*					*	*	*
processing time calculation	*	*	*	*	*	*				
TOTAL	*	*	*	*	*			*		

1 = index for shape and position of the surfaces,
2 = number of different flat surfaces,
3 = index for heat treatment,
4 = number of dimensions on the drawing,
5 = index for precision,
6 = number of holes,
7 = number of dimensions with tolerances,
8 = ordering of the outer diameters,
9 = maximum outer diameter,
10 = number of different types of tolerances.

The determination of raw stock turned out to be an almost constant factor ranging between 2 and 6 minutes. Through e.g 'the number of dimensions on the drawing' and the 'different process specific shapes' the shape complexity of the part determines the time needed for the by far most time consuming task (processing time calculation). The second most time consuming task (specification of the process variables and tooling choice) is mainly determined by the processes other than turning. This indicates that here too the shape complexity of the part is a main factor. Given the different objective of the results discussed here this can not be accepted as a confirmation of our hypothesis. However, it is not in contradiction to our hypothesis either.

Of the organizational variables only the degree of automation of the information carriers was found to be significantly related to the time needed for making a process plan. Although the degree of automation of the aids and the qualification of the personnel in process planning were found to be related to this variable, these variables were not significantly related to the independent variable themselves. In view of our hypothesis it is also possible to explain this effect the other way round: simple tasks can be automated and thus automation is related to the time needed for making a process plan.

3. Results

3.1. Analysis

If the necessary conditions are fulfilled, the relations investigated here can be found through Multiple Regression Analysis (MRA) of uncertainty scores per task as a function of translation difficulty scores and process variable interdependence scores for that task. In MRA a function is fitted to the independent and dependent variable values. This function has the following form:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + e$$

In this formula β_0 is the intercept, $\beta_1 x_1$ to $\beta_n x_n$ are the independent variables with their parameters and e is an error factor. The hypothesis that the parameters of the independent variables and the intercept are equal to zero are tested. Here y is the task uncertainty in process planning tasks, the x's are the independent variables VERTMOEI, AFHANK, BEHAVAFT and TASKNEW (see section 1.4).

In Multiple Regression Analysis, the percentage of variation in the dependent variable that can be explained by the independent variables, which are derived from theory, is usually judged as satisfactory (Regterschot, 1992) when the percentage is between roughly 50 and 80%. Below 50 % the independent variables do not relate to the dependent variable in any relevant degree. Above 80% the independent variables are so strongly related to the dependent variable that an erroneous/trivial relation should be expected. In our case, an explanation of fifty to sixty percent of the variance in the process planning task uncertainty would be quite acceptable. No quantitative relation between the independent and the dependent variable is sought here. It is claimed that some of the important variables which explain task uncertainty have been found. Therefore, a 50 to 60% score would be sufficient to accept the hypothesis.

For each of the four manufacturing processes studied the analysis of results is presented below. The conditions for application of MRA were checked. The scatterplots (see appendix 1) of residuals against predicted values indicate that linear regression was indeed sufficient here: the scatterplots all show clouds of points around the 0-axis.

3.2. Conventional deep-drawing

In both companies where conventional deep-drawing was investigated, there turned out to be two major (groups of) process planning tasks: tooling specification and determination of the other process variables. The former task is carried out by tooling engineers. The second group of tasks was found to be carried out by operators possibly assisted by specialist process planners. This is a form of lateral relations (to cope with task uncertainty) as described by Galbraith (1973). Tooling specification is always the first task to be carried out which can be understood because it is potentially the most time consuming and costly task (see also Hayes et al. (1989) and chapter 2).

The process matrix for conventional deep-drawing and the correlations between the dependent variable UNCERPRO and the independent variables are given in appendices 2 and 3 respectively. The correlation between UNCERPRO and the measurement scales of part characteristics and process variables is quite significant over all tasks. This correlation is less strong for the interdependence of process variables. The correlation with the sort of task is insignificant for this manufacturing process. These correlations can be explained by pointing at the shapes of the parts processed in conventional deep-drawing. These are mostly parts with very irregular 3D shapes. As becomes clear from appendix 2 the part's shape influences process variables that also are of a continuous and nominal character. These process variables influence both the process planning tasks. This explains the strong influence of VERTMOEI and the non-significance of the kind of task.

Based on the correlations, the independent variables VERTMOEI and AFHANK were brought into the regression model respectively. The consequences of bringing in these variables are summarized in appendix 4. Although the addition of AFHANK is slightly over the edge of significance, the adjusted R^2 shows that AFHANK and VERTMOEI together explain around 60% of the variance in UNCERPRO: a satisfying result. The independence of VERTMOEI and AFHANK was checked through collinearity analysis (see appendix 5). This analysis shows that independence can be assumed.

Of the variables constituting UNCERPRO the following can be said. The time spent on tool specification (by a tooling engineer) ranges from one to eight hours in one company and from 8 to 40 hours in another company. The fact that the latter company makes larger and more complex parts explains the different ranges. The specification of the other process variables is done by the operator and took 3 hours for the easiest piece and 8 hours for the most difficult one in the first company. Comparable figures were found in the second company. It is remarkable that for the more difficult parts the operators are always assisted, at least by the tool designer. This is again a form of lateral relations between organization units set up to cope with task uncertainty (Galbraith, 1973). The amount of time spent process planning tasks for deep drawing sheds some light on the findings of Almenraeder (1983) presented in section 2. Almenraeder found a maximum of two hours to be spent on process planning for milling, turning, grinding and drilling. Rework can also take considerable time in conventional deep-drawing: from 8 hours for the most difficult of the three parts in the first company to 28 to 110 hours in the second company. Especially the most difficult parts would be planned by experienced process planners. This confirms the insignificance of formal training or education of process planners as found by Almenraeder. The experienced planners are assumed to have an experience of around 12 years. This can be seen as the use of slack resources as described by Galbraith (1973).

3.3. Rubber cushion deep-drawing

Like for conventional deep-drawing, in rubber cushion deep-drawing two main groups of process planning tasks exist: tooling specification and the determination of the other process variables. The former task is carried out by tooling engineers. The second group of tasks is carried out by operators possibly assisted by specialists (lateral relations). Like for conventional deep-drawing, tooling specification is always the first task to be carried out.

The process matrix for rubber-cushion deep-drawing is given in appendix 6. The correlations between the dependent variable UNCERPRO and the independent variables is given in appendix 7. Here AFHANK is the most strongly correlated variable while VERTMOEI is on the edge of significance. Again the kind of task or the influence of part behavior after processing was insignificant. Based on the correlation coefficients, the independent variables VERTMOEI and AFHANK were brought into the regression model respectively. The consequences of bringing in these variables are summarized in appendix 8. The 60% explanation of task uncertainty is satisfactory. However, a check of the independence of VERTMOEI and AFHANK through collinearity analysis (see appendix 5) shows that independence can not be assumed for this manufacturing process. This can be explained by the fact that the more difficult (more irregularly shaped) parts are drawn negatively. In negative drawing, which is comparable to conventional deep-drawing, interdependence of process variables is much stronger than in positive drawing (the folding of sheet-metal over a die).

On the constituting variables of UNCERPRO the following can be said. The time aspect on tooling specification ranges from one half to 4 hours. For the tooling specification for the more difficult parts first the assistance of experienced colleagues than the help of specialists is sought. Again, the results presented by Almenraeder are in sharp contrast to what was found for this process. The design of specific tooling is the most time consuming factor, not the determination of the other process variables. The experience needed for planning the most difficult parts was estimated at about 6 years.

3.4. Die casting

The process matrix for die casting is given in appendix 9. As can be seen there are some relations and strong interdependencies between process variables and part characteristics of continuous and nominal character: the parts shape, the shape of the casttree, the partition of the die etc.

The correlations between the dependent variable UNCERPRO and the independent variables is given in appendix 10. The strong correlation with VERTMOEI is not very surprising, given the above. The low correlation with AFHANK is somewhat surprising. One would expect this correlation to be higher based on the many relations between process variables.
Based on the correlations, the independent variables VERTMOEI and AFHANK were brought into the regression model respectively. The consequences of bringing in these variables are summarized in appendix 11. The

significance of bringing AFHANK into the model confirms that this variable is of importance on top of VERTMOEI. The 56% explanation of the variance in UNCERPRO is satisfactory but is not as high as one would expect given the character of this manufacturing process.

The time needed for the different process planning sub-tasks was as high as 24 hours for the specification of the tooling. The experience that a process planner needs for the most difficult part was indicated as 6 to 8 years. The latter confirms the findings of Almenraeder presented in section 2. Like for deep-drawing and for rubber-cushion deep-drawing, the former shows that the results of Almenraeder strongly depend on the manufacturing processes he chose for his research.

3.5. Milling

The process matrix for milling is given in appendix 12. Given the fact that, for this process, manufacturing process variables can be related to part features, one would expect the influence of AFHANK to be low. This is the case as is shown with the correlations between the dependent variable UNCERPRO and the independent variables (in appendix 13). Based on these correlation coefficients, only the independent variable VERTMOEI was brought into the regression model. The consequences of bringing in this variable are summarized in appendix 14. This variable alone accounts for 47% of the variance in UNCERPRO. It can be expected that the influence of the determination of manufacturing resources will be far more important for this process than for the other processes. In the companies investigated for conventional and rubber-cushion deep-drawing and for die casting there generally was no alternative resource. In the companies investigated for milling there generally was a choice of two or three alternative machines.

For milling four process planning sub-tasks were discerned: the specification or selection of the tooling required, the determination of feeds and speeds, the determination of quantity and spots for the application of auxiliary materials, the determination of the tool trajectories. Seeing the process matrix, in case of part shapes that are irregular and that can not be broken down into known features, all four tasks can be expected to have significantly higher uncertainty degrees. The time that is spent on the different tasks can indeed be measured in terms of minutes in case of known features. In case of parts that do not have known features the time needed for a sub-task could get to a maximum of 6 hours (determination of feeds and speeds). This indeed confirms Almenraeder's results for this manufacturing process. The experience that is required of a process planner was indicated as three years for the most difficult parts. As found by Almenraeder there might not be a direct link between the time spent on making of process plans and the formal education of the planner. However, the higher degree of automation in process planning for milling compared to the other processes discussed here might be the reason that education (to use automated aids) is more important for this process.

4. Discussion

The variable BEHAVAFT could only be measured for the manufacturing processes milling and rubber cushion deep drawing. Consequently, the number of cases in which it played a role is too small to allow any conclusions and correlations are very low.

The collinearity analyses (appendix 5) show that only for rubber cushion deep drawing there seems to be interdependence between the two variables VERTMOEI en AFHANK (the variance proportions of both variables are high on the third Eigenvalue). In the other three cases there is some collinearity but not very strong. Taking into regard the measurement scales of the two variables this is not very surprising: the variables are measured by means of the highest difference between part characteristics and process variables measurement scales and amongst process variables measurement scales respectively. The presence of a process variable with low measurement scale (nominal, ordinal), which contributes to both variables, will change the result in the direction of higher scores.

The conditions for application of the MRA were fulfilled by all the data. The scatter diagrams in the appendices all clearly show clouds of points and not a relation which would point at a violation of the linearity demands.

5. Conclusion

The results presented above can be seen as a confirmation of the hypothesis. For all manufacturing processes, the variables VERTMOEI and AFHANK explain 50% to 60% of the variance in UNCERPRO. Only in the case of milling AFHANK does not contribute to the explanation of the variance. This is not very surprising given the process matrix of milling. This matrix indicates that there are few interdependencies in milling and that these few interdependencies are between variables on high measurement scales (interval, ratio). Since in practice plants which do milling operations have more than one machine, the machine choice can be expected to contribute relatively more to task uncertainty in process planning for milling than in the case of the other processes investigated here.

So, the interdependence of manufacturing process variables and the measurement scale of part characteristics and manufacturing process variables are relevant IE & MS concepts. These concepts give the ability to relate manufacturing technique to task uncertainty which is a variable with IE & MS relevance (see chapter 4). The use of lateral relations between organization units and the use of slack resources were found to be amongst the measures to cope with task uncertainty due to the interdependence of process variables and to the measurability of process variables and part characteristics. In that way a link from technique to managerial variables such as skills needed for a task and the organization of tasks has been made. This enables a judgement of manufacturing technique without deep traditional technical knowledge. The order of magnitude of the effect of the interdependence of manufacturing process variables and the measurement scale of part characteristics and manufacturing process variables is different for different processes (and perhaps companies). Compare for example the indications of the experience needed to plan difficult parts. For all process, however, task uncertainty increases with these variables and that is what is claimed on the basis of the figures presented here.

CHAPTER 6.

The machine choice in process planning: manufacturing resources and task uncertainty in process planning.

In chapter 2 the control situation of process planning was sketched. Per process step, process planning can determine the material for the part to be planned, the values of the variables of the manufacturing process with which the part should be made and the manufacturing resources that establish the manufacturing process. Based on some observations of the potential impact on IE & MS aspects of process planning, the influence of the translation of parts characteristics to values of the manufacturing process variables on the task uncertainty in process planning was chosen for further investigation in chapter four and five.
In that investigation (field experiment) it was assumed that, for the manufacturing process that a process planner works on, there is one machine that can establish the process. The machine choice can only add to the uncertainty in process planning if the process planner is aware of (one or more) alternative machines for establishing the manufacturing process. So, in chapters four and five, the influence of the machine choice on process planning uncertainty was ruled out. In reality, this assumption will not always hold.

In this chapter, the task uncertainty in process planning, due to the machine choice, is investigated. This is done under two assumptions. First, there is more than one machine that can establish a manufacturing process for a part. Second, the process planner knows that these alternatives exist and is able to evaluate the capabilities of the different machines.

As in the earlier chapters, the investigation is done against the background of small batch manufacturing (see also chapter 2): process planning is the function that translates a frequent stream of part specifications into instructions for an existing set of machines on which the parts will be made according to recurring production orders.

The investigation of task uncertainty in process planning, due to machine choice, here has the form of a systematic analysis of the choice situation and the choice criteria. In section one, the choice situation is analyzed and defined. Section two discusses some observations on the place of the machine choice in the process of process planning. In section three the technical criterion is worked out. For the economical criterion this is done in section four. The dynamics of the choice situation are treated in section five. Section six presents some conclusions.

1. Analysis and definition of the choice situation

For reasons discussed earlier (chapter four) the uncertainty in a certain task is of interest to IE & MS observations of that task. So, concerning the choice of a machine for making a part, the focal point has to be how this choice adds to uncertainty in process planning tasks.

As said, in this thesis process planning is seen as a control task. From this it follows that process planning needs models of the machines' capabilities, their availability (that are valid over the time horizon of the decision) and their match with the process variable values.

Schematically, this gives the following picture of the machine choice in process planning: the process planner matches some sets of process variables with the capabilities of alternative machines thus satisfying the goal of a 'good' part plus possible additional goals. This matching is finalized in the specification of machine parameters and operator instructions.

Clearly, there are process planning situations that do not fit in this picture, even within small batch manufacturing. First, the situation where there is only one machine that can establish the process. This is often the case in smaller companies that specialize in manufacturing with processes which ask expensive dedicated tools e.g. deep drawing. Frequently, such companies exploit only a few presses that do not overlap much in their capabilities (maximum load etc.). One of the companies in the field experiment, a sheet-metal manufacturer, for example, exploits one deep drawing press and one rubber cushion deep drawing press. It seems that for sheet-metal forming processes this situation is quite normal.

Second, one can imagine a situation in which, on basis of certain part characteristics, parts are allocated to 'dedicated' machines or production lines (see chapter 2). A good example is given by one of the companies in the experiment where die casting of certain materials is only carried out on certain machines. Such qualifying variables will have to be known before a machine can be selected and hence these variables determine the place of the machine

selection in process planning.
Third, there can be some freedom of choice in the division of process steps over diverse machines. For example a part can be processed completely on an FMS or, possibly on basis of capacity considerations, certain process steps can be carried out on other machines.

In the rest of this chapter these situations are ruled out. In other words only machine choice situations are considered in which the process planner can choose between two or more machines that can be used to carry out a process step for the part that he/she plans.

2. The place of the machine choice in process planning

The build-up of this thesis might suggest that in process planning the values of the variables of a manufacturing process for a part are always completely determined before a machine is chosen to carry out the process. This suggestion, however, is not correct. There often is some freedom 'within' a manufacturing process to make a part with different 'sets' of values of the process variables. This makes that the machine and the manufacturing process variable values can be determined iteratively (see also: van Luttervelt, 1989). Most authors (Hebbeler (1989), Baberg (1980), Almenraeder (1983)) discern a rough planning phase (processes) and a detail phase (machine choice and machine specific variables). The place of the machine choice further seems to depend on the criteria that one wants to take into account making the choice and the information that is needed for scoring these criteria.

The obvious first criterion in the machine choice is that of technical feasibility. A machine has to be able to deliver the values of the manufacturing process variables necessary for carrying out the process. As a.o. Van Houten (1991) and Hebbeler (1989) observe there is also an economical and a capacity planning criterion involved in the machine selection. The economical criterion refers to the costs that are associated with the manufacturing of a part on a specific machine. The capacity planning criterion refers to the availability of a certain machine and the balancing of capacity demand over different machines. Process planning can establish load balancing amongst machines by taking into account the jobs that have already been planned on a certain machine.

Some comments can be made regarding these criteria. The concept of 'machine capacity' is somewhat narrow for our purposes. In chapter one a machine was defined as: 'the installation aimed at providing the energy and the capability of moving and positioning tools'. This definition does not cover all of the elements of the manufacturing process as given in chapter four. Notably, the supply of auxiliary materials is not covered. In some cases this will be done by the machine in other cases by the operator. As noted in chapter two, the process planner not only specifies machine parameters but also operator instructions. Consequently, not only the machine but also the operator with his/her knowledge may be determinant for the output of an operation. If a specific operator represents a unique capacity, e.g. a skill of supplying auxiliary material in the right way, the process planner should also consciously plan operator capacity.

On top of the technical, economical and capacity criteria, other criteria can also influence the choice of a machine. From a marketing point-of-view it might be favorable to offer e.g. NC-machined parts instead of conventionally made parts. Apart from 'objective' criteria in the machine selection it might even be relevant to also take into account subjective criteria in this choice. The personal preference or incomplete knowledge of a planner can contribute to the choice for a certain machine. One process planner in a company of the field experiment remarked that some of his younger colleagues tend to plan parts (automatically) on the newer machining centers and not on the older machines. The marketing criteria and the subjective criteria in machine choice will not be discussed any further here. The technical, economical and capacity criteria for machine choice will be further worked out in the sections below.

3. The technical criterion

The uncertainty in the machine choice due to the technical criterion is determined by the difference between:

- the information available to the process planner:

  the energy, the relative movement of tool and workpiece, the auxiliary material that the machine has to supply, the blank to be transformed, the tools needed,

- the information needed:

  the range of each of the parameters of the machine on the above mentioned process variables.

For three important groups of manufacturing processes in the DIN8580 classification ('Urformen', 'Umformen' and 'Schneiden') the parameters of a machine will now be treated.

For sheet metal forming processes (representing: Umformen), like deep drawing, the machine parameters generally have the following character:

- energy: load,
- relative movement: length of the linear movement of the ram,
- auxiliary material: the supply of lubricant needed between tool and sheet metal,
- blank: the maximum size/thickness of the sheets that can be processed,
- tools: three dimensional shape, especially made for a part.

For these processes the auxiliary material supply (spots where lubricant is needed) seems to be the only parameter that can only be operationalized on a nominal continuous scale. If presses have this parameter it will be something like a nozzle that does not offer very precise tuning of the lubricant supply. Full mechanization of this parameter, however, is rare. The tools (die, mould, down-holder) are especially made for a part so only the interface of the machine with the tool and the maximum size of the tool are parameters of the machine.

For full forming processes, like die casting, the machine parameters generally have the following character:

- energy: maximum closing pressure, die temperature and plunger speed,
- relative movement: opening length of the dies,
- auxiliary material: pump capacity and nozzle for cooling fluid and supply of discharge fluid,
- raw material (blank): the maximum plunger content,
- tools: especially made for the part.

For these processes again the supply of discharge fluid (spot, quantity) is the only parameter that is hard to operationalize. In one of the companies in the field experiment customized nozzles are made to give a machine this parameter. In that case a precise tuning of the lubricant supply is built into the machine and this machine parameter is reduced to pumping speed. The tool (mould) is especially made for a part so only the interface of the machine with the mould and the maximum size of the mould are parameters of the machine.

For machining processes, like milling, the machine parameters generally have the following character:

- energy: spindle speed and feed,
- relative movement: tool path,
- auxiliary material: the lubricant/cooling fluid,
- raw material: the maximum size of the blank that can be processed,
- tools: the set of cutting tools on the machine.

For these processes the availability of the generic tools on a machine is part of the technical criterion. The parameter 'relative movement of tool and base stock' can be hard to operationalize if complex 3D movements or the possibilities of collisions (tool to part) are to be considered. However, in many applications these movements are not quite so complex. Tools can be a fixed set per machine. Otherwise the interface (tool-holder) determines the parameters here. So, it is not surprising that Van Houten (1991) as well as Vancza & Markus (1991) conclude that the technical machine choice for machining processes is relatively simple.

Assuming that the parameters of alternative machines have been mapped and that they are available to the process planner, uncertainty in process planning due to the technical machine choice can be reduced:
- by limiting the amount of information needed: limiting the number of machines that have to be taken into account,
- by enlarging the available amount of information: generating more processing alternatives for making the part.

The former refers to higher level decisions that allocate certain machine parameter ranges to certain machines. Such an allocation decision can itself be technically motivated. By allocating certain ranges economies-of-scope can be achieved. In the example that was given earlier: certain materials (metals) were allocated to specific die casting machines. The feeling is that the constant temperature in the machine (melt temperature of the metal) is positive for product quality.

The latter refers to presenting more than one combination of process variables per machine that produce the desired part. Usually, a manufacturing process has some freedom-of-choice as to how exactly a certain part can be processed. Drilling a hole e.g. can be done with a combination of (smaller and larger) drills. A combination of drills e.g. offers the possibility to use machines with more or with less power.

4. The economic criterion

The function of the economic evaluation of the machine choice is to provide a common denominator for all the effects of the different alternatives. This asks for knowledge of the effects and a translation mechanism into economic (financial) terms.

How exactly the effects of the choice of a certain machine are translated into an economic calculation depends upon the economic calculation method chosen. The method that is to be chosen to translate the effects of decisions into economical terms is subject of considerable discussion in the literature (see e.g. Kaplan, 1991). Broadly speaking two approaches can be discerned. The first is known as full costing and (stated simply) advocates that in a decision in which capacity is allocated not only the costs of the application of that capacity (in the future) should be taken account but also the costs of the purchasing of that capacity. The second approach is known as the relevant costing. This approach advocates (stated simply) that once a capacity is purchased it's price, the cost of purchasing, should be considered as 'sunk costs'. So, in the relevant cost approach there is no principal difference between a conventional lathe and a sophisticated machining center (which can be assumed to be far more expensive). As Wouters (1992) shows, however, managers tend to use the full costing approach when allocating capacity.

It is assumed here that the full costing approach is used as the economical criterion for the machine choice in process planning. With the acceptance of the full costing principle, the economic criterion in process planning can be summarized as:

> min! {(per part costs of machine usage (depreciation + running costs)) + (investments needed to produce the particular part on the particular machine divided by the estimated total number of parts to be made)}

Uncertainty due to the economical criterion in the machine choice in process planning now results from the fact that not all of the information that is needed for this calculation is known precisely on the moment of machine choice. First of all there is an interaction effect: the allocation of the job to a certain machine influences current jobs and the allocation possibilities of future jobs. This not only has logistical implications but can also have economical implications. Second, the performance of a machine on a certain job is not known precisely since the job has not been carried out yet and the estimation of the performance can be quite difficult. Third, if considerable machine specific investments are to be made (e.g. specific fixturing) there is also uncertainty as to the precise height of the investments.

In order to reduce the uncertainty a decision strategy can be applied. In their process planning system model Vancza and Markus (1991) apply a two step approach in which first the number of set-ups and second the number of tool changes is minimized. Hayes, Desa & Wright (1989) only use the number of set-ups as a criterion. Van Houten (1986) proposes a strategy based on calculating the costs of tool management, tool-changing and machining. These decision strategies all try to reduce the number of available alternatives by focussing on the main contributors to costs.

Another approach would be to improve the available information. This would mean getting better insight into the interaction with other jobs and the height of the investments that are needed (see: Wierda (1990), Baumann (1982)). Getting better insight into the interactions with other jobs might be very difficult for the simple reason that in small batch manufacturing future jobs and their due dates are unknown. The estimation of the investments needed for a certain job asks for finding relationships between part characteristics and machine specific costs.

5. Dynamics of the machine choice

As said, the allocation of a job to a machine implies a restriction on the allocation of other (future) jobs to that machine. This interaction has to be taken into account if the availability of resources is to be guaranteed. For process planning this means two things:

- at the moment a job is assigned to a machine the capacity criterion has to be taken into account specifically,
- if future jobs are allowed to break into the earlier decided upon allocations, alternative process plans may be necessary for the parts that are reallocated.

If future jobs, or e.g. rush orders, are allowed to break into earlier allocation decisions, this can have serious consequences for the production of the part that is to be reallocated, e.g.:

- the alternative machine might not be able to do the complete operation the original machine did: the operation has to be divided over more machines,
- the alternative machine might request other tools or fixtures which requires much preparatory work,
- the degree of automation per machine might differ which asks for different control information,
- the reallocation of a part to another machine might necessitate reallocation of more parts.

Such changes and interactions add to the uncertainty in process planning since process planning does not know which process plans to make or which tools, fixtures etc to offer. In general there are two ways in which process planning can react to these changes:

- feed forward: by making alternative process plans (for the alternative machines) in advance of the necessary changes,
- feed back: by making alternative process plans on the moment that the necessity of a change over of a part to another machine becomes necessary.

However, these two strategies are not possible in every production environment. The allocation of a job to a machine is the moment when process planning and production planning come together. So, whether or not the reallocation of a part is possible and can be prepared by process planning, also depends on the production control philosophy that is advocated in production planning. This control philosophy determines the way capacity limits are considered. For the three main production control philosophies (Manufacturing Requirements Planning (MRP), KANBAN and Optimized Production Technology (OPT)) the ideas on the allocation of parts (jobs) to capacity (machines) will now be treated in the framework of how these philosophies treat capacity.

In MRP the Master Production Schedule (MPS) represents an agreement between a.o. Production, Planning and Marketing on the amounts of each product(-group) that will be made in the coming planning periods. The MPS can be confronted with the available capacity in production in the so-called Rough Cut Capacity Planning. Roughly speaking this a check whether, per planning period, the MPS times the production rates exceeds capacity or not. If so, the timing of the jobs has to be changed or capacity should be added. A different allocation of jobs to capacity is not explicitly taken into account in MRP, but it would fit in the total scheme of reevaluation of the MPS or the production capacity in case of capacity shortages. In that case process planning feeds forward. In the MRP planning (on the short term) capacity is not a criterion. However, rush orders or break downs can disturb a production program in MRP. The mechanism in MRP to counter such disturbances is the rescheduling (in the time) of jobs. A rescheduling to other capacity often is not a mechanism in MRP, but it would certainly make planning more robust. In that case a change over of jobs to other machines has to be done on the short run (feed back).

A central element in KANBAN is the balancing of production capacity and demand. Only in such a balanced situation it is possible to create the continuous and smooth flow of products, controlled by the pull of the KANBANs, that is the aim of this philosophy. In such an environment the balancing of capacity by clever allocation certainly fits. A quick change-over of parts to other machines however clearly does not fit in. A sudden change over of a part to another machine would evoke interactions with the other tightly balanced production lines and the whole system could break down. In case of break-downs the KANBAN philosophy is that the problem should not be hidden but should be felt and lead to improvements that prevent break downs. It seems therefore that KANBAN explicitly denies the possibility of quickly changing to other capacity when break-downs occur. Only a built-in flexibility in which alternative production locations are explicitly indicated on the KANBAN is acceptable. So, only feed forward by process planning can be accepted in a KANBAN environment.

OPT aims to maximize the throughput of a production system. As explained in chapter 2, the maximum utilization of available capacity should be established by maximizing the throughput of the bottle-neck capacity. In such an environment process planning should be especially well aware whether or not it plans for a bottle-neck. The operations on a part downstream or upstream of the bottle-neck have sufficient capacity and a change over to another machine will never be necessary there (theoretically). Only in the framework of avoiding idle-time on the bottle-neck, due to breakdowns upstream, a prepared change-over to another machine or to other tools would be helpful. As Krause (1989) argues, parts that are produced on an FMS (often a bottle-neck capacity) should always be given several process plans in order to use the flexibility of the FMS for securing a high output. With these alternative plans the consequences of e.g. a tool that breaks can be countered by using another tool and (hence) other plans.

An unprepared change-over to another machine from a bottle-neck is not assumed since this would limit total system throughput. Planned flexibility to protect the bottle-neck against the effect of break-downs (e.g. the use of other tools or the use of non-bottle-neck capacity) would fit into the OPT philosophy.

One of the Computer Aided Process Planning systems that are explicitly linked to production planning is PART (van Houten, 1991). The goal of the planning module in this system is to maximize the chance that the required capacity (for a production program) is indeed available in the planning horizon. The actual allocation of a set of orders is evaluated on the smallest 'evaluation time'. This is a measure calculated from:

- the fixed evaluation time: the sum of estimated machining, tool changing and pallet changing times with an addition for weighted time for indirect tasks,
- the variable evaluation time: a penalty time on tool changes,
- the period evaluation time: a penalty for (positive and negative) due date deviations.

This evaluation time criterion seems to refer implicitly to an MRP-like production control philosophy. The total time for a complete set of jobs for the whole shop is evaluated. The line balance idea of KANBAN is not there: the capacity loading of different sets of capacity is not compared. Neither is the bottle-neck idea of OPT represented in the system: a total loading over the whole shop is the criterion not a maximum loading of one resource.

6. Conclusions

It can be concluded that the technical machine selection does not influence process planning uncertainty strongly (see section 3). This is due to the fact that most machine parameters can be readily operationalized. Only the auxiliary material supply for some processes is difficult to operationalize. In situations where the operator has to provide this 'machine parameter' this adds to the uncertainty since it is difficult to operationalize such skills.

The economic and the logistic criterion in the machine choice add much to the uncertainty in process planning.

For the economic criterion this is mainly due to the unknown performance of a machine, the unknown investments for tools, fixtures etc. and the cost effects of reallocating other jobs. This asks for a choice strategy which essentially reduces the uncertainty in the economic criterion by looking at single cost-determining factors (e.g. minimization of the number of set-ups).

For the planning criterion the uncertainty is mainly due to the interaction (in capacity utilization) of the job that is to be planned with other jobs. However, this effect depends on the control philosophy in production. OPT and KANBAN only seem to allow for feed forward balancing/optimization of capacity usage. This can be achieved with manageable calculation effort.

CHAPTER 7.

Conclusions

In this chapter conclusions will be drawn from the research presented in earlier chapters. The idea is to elevate the scientific results to the level of IE & MS implications.

The first section concludes on the contents of the process planning activity and the changing role of process planning in the business climate of today. In section two, the knowledge and skills needed for process planning for different processes, parts and resources is sketched. This of course has implications for the appropriate training and personnel policies. In section three the possibilities to automate process planning are treated. The organization and control of the process planning tasks dependent upon part characteristics and the character of the manufacturing process is explained in section four. Section five, finally, treats the choice of manufacturing processes in design in view of the research results.

1. The process planning process: mapping and translation

As became clear from the research presented in this thesis, process planning for mechanical manufacturing consists of a mapping step and a translation step. In the mapping step the part geometry and the other part characteristics are mapped onto characteristics that are meaningful for manufacturing (manufacturing features) i.e. characteristics from which the value of manufacturing process variables can be determined. In the translation step, this manufacturing interpretation of the part is translated into the appropriate values of the manufacturing process variables, into the choice of a machine for making the part and into operator instructions.

As was shown from the literature, in the business climate of today the control and reduction of the costs and the time associated with the design/development activities becomes increasingly important. This asks for rationalization of the total design/development process. This means that a design department can no longer 'throw a design over the wall' leaving process planning with the problem of making the part that is not adapted for ease of manufacturing. On the other hand process planning can no longer afford to provide production with less than timely and right instructions that can be adapted to unexpected changes in production. Changing the interfaces between on the one hand detail design and on the other hand process planning and production is necessary in a business environment of increasing speed of product change.

2. The process planner: knowledge, skills and training

The research presented in this thesis shows that the uncertainty in process planning tasks differs for different manufacturing processes, parts and resource availability.

Task uncertainty due to the manufacturing process was found to be low if:

- both parts and process variables can be described on an interval or ratio scale,

or if:

- part characteristics can be broken down in discrete elements that can be related to manufacturing process variables independent of each other.

Under these conditions, formalization of process planning knowledge can be achieved by finding the relations between manufacturing process variable values and part characteristics. For some processes and parts these conditions do not apply or apply only for some process variables. This makes the build-up of formalized process planning knowledge very difficult. This influences the appropriate training and selection policies for process planners. For processes/parts that can be formalized to a high degree, process planners with programming skills are to be trained. For the less formalizable processes/parts the build-up of hands-on experience with the process as well as associative thinking is more important.

If the availability of manufacturing resources and their performance is highly predictable, process planning knows which resource will be used and can exactly specify the process plans for a part and a certain resource. If the predictability is low, process planning (partly) has to be done right before the actual moment of production because only then the resource to be used is known. Such last moment process planning asks for improvisation skills and the ability to generate plans quickly under time-pressure.

3. Organization and control of process planning

The literature learns that task uncertainty is a main determinant for the best way to organize and control tasks. It was shown that the uncertainty in process planning tasks increases:

- the more the factors that increase the difficulty of formalizing process planning knowledge (mentioned in 2.) apply,
- the less the predictability of production orders combined with a production control philosophy that allows reallocation of jobs to capacity.

High task uncertainty asks for organizational measures. Galbraith presents four organizational measures to cope with uncertainty (see chapter 2). Also a domain of process planning uncertainty may be defined (see figure 1).

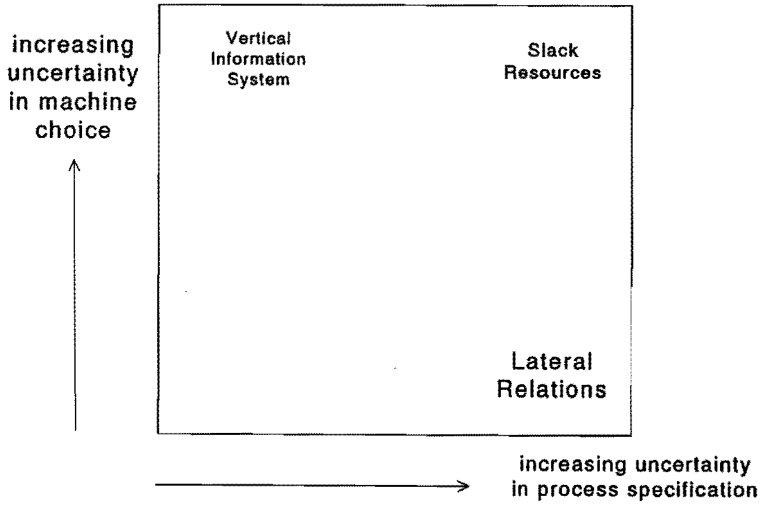


Figure 1. The domain of process planning uncertainty and possible measures to cope with this uncertainty.

If a process can be formalized but predictability of production orders is low, organizational measures might be taken to increase the availability of information on future orders. This asks for a vertical information system that improves demand forecasts and communicates them.

If the possibilities for formalization of process knowledge are low and the production orders can be forecasted well, horizontal integration of tasks seems appropriate. By horizontal integration specialists of the diverse functions can be brought together to generate the difficult-to-formalize knowledge.

If both the formalization of process knowledge is difficult and the availability of manufacturing resources is uncertain the only organizational measure left seems to be 'slack resources'. This means that the uncertainty is planned for by reservation of extra time and capacity for process planning.

If both the process knowledge can be highly formalized and the availability of manufacturing resources is highly predictable, process planning and production planning can be strictly separated. Process planning can make process plans on machine level immediately ('off-line') and hand them over to production planning.

Also, in the environment of small series manufacturing, a clear view of the process knowledge in a company, and of the resource availability, are to be applied as the criteria for accepting orders. If the order consists of part(s) that have characteristics that are outside the company experience, this will make it difficult to control delivery-time and costs of the first series.

4. Process planning automation

With the difficulties to formalize process knowledge the automation of process planning gets more difficult. Therefore, it is no surprise to see that the vast majority of Computer Aided Process Planning systems have been developed for machining processes (see a.o. Alting and Zhang, 1989). On the one hand formalization of these processes is easier than of most other processes, on the other hand (and as a consequence) these processes have been studied most intensively.

Known applications of computer aided techniques for forming processes (almost) all have the character of expert systems in which the (case based) knowledge of experienced process planners is combined with some very simple calculations (Maloney et al., 1989). The output of CAPP systems can be as complete as a full specification of NC programs and operator instructions. The output of the known expert systems more have to character of do not's than of useful operator instructions let alone NC programs (Gadh et al. 1989).

5. The choice of machines and processes in design

Apart from the measures presented above, uncertainty in process planning can be dealt with by adapting the input to process planning from detail design. If the part information leaves some freedom to process planning to adapt the part to fit process planning experience this is a way to reduce uncertainty. So, at least from the stage of subsystems (or subassembly) design in the design process the choice of manufacturing processes and machines for the manufacturing of the parts should be taken into account. In order to avoid long iterations in the design process, the design should be tuned to the manufacturing processes or leave enough freedom to detail design and process planning to do so. The idea of the conceptual description of a part is a basis for such an adaptable part description.

Manufacturing processes have specific characteristics concerning the possibility to build-up process knowledge: the possibilities to learn by repetition or by intra/extrapolation of earlier experiences. The less a process offers these possibilities, the more the need to leave freedom to detail-design and process planning to adapt the part design for ease of manufacturing. This is in concordance with the 'design for analysis' idea presented by Suri & Shimizu (1989). They plea for designing products so that their manufacturability can be analyzed.

Suggestions for further research

The interdependence of manufacturing process variables and the measurability of process variables and part characteristics were found to be IE & MS aspects of manufacturing processes. A more detailed study of these concepts, however, would certainly increase the insight a lot. A closer study of the interdependence of process variables, as expressed in process matrices, could for example lead to a redefinition of the manufacturing feature concept for processes with strong interdependencies. If blocks of process variables could be separated in the matrix this block could be considered as a manufacturing feature in it's true sense.

Another direction for further research could be the operationalization of the concepts of this thesis in a control instrument for process planning. In this direction a start has been made (see; Florusse & Clausing, 1992).

A last suggestion can be further research to map the technological capabilities of a company with the help of the concepts presented in this thesis. Specifying a companies experience in terms of process variables, part characteristics and machine parameters and mapping these on technological limit values might be a sensible way to picture a company's technological capabilities.

REFERENCES

Akao, Yoji
1990 QFD: integrating customer requirements into product design. Cambridge: Productivity Press.
Aken, Joan E. van
1991 Organisatiekunde, uil of jonge zwaan. (in Dutch) Eindhoven University of Technology: Inaugaral Speech
Almenraeder A.
1983 Beitrag zur Bestimmung des Zeitaufwandes fuer die Funktion 'Arbeitsplanerstellung' im Maschinenenbau. (in German) PhD. Thesis, Aachen: RWTH
Alting, Leo
1982 Manufacturing Engineering Processes. New York: Marcel Dekker.
Alting, Leo and Hongchao Zhang
1989 "CAPP: the state-of-the-art survey." International Journal of Production Research, 27, 4: 553-585.
Amelsfoort, Pierre van
1992 Het vergroten van de bestuurbaarheid van produktieorganisaties. (in Dutch) PhD thesis, Eindhoven: Eindhoven University of Technology.
Ashby, Ross W.
1958 Introduction to Cybernetics. London: Stamford.

Baberg Th.
1980 Rationalisierung in der Arbeitsplanung unter Beruecksichtigung dynamischer Unternehmensveränderungen und der Auswirkungen auf die Fertigungskosten. (in German) PhD thesis, Aachen: RWTH
Baumann G.
1982 Ein Kosteninformationssystem fuer die Gestaltungsphase im Betriebsmittelbau. (in German) PhD. thesis, Muenchen: University of Technology
Berger, Gus
1985 "Lead Time Reduction: Management's best competitive strategy." APICS conference proceedings: 135-139
Black I.
1989 "Product innovation and mechanical CAD." CAE Journal, October: 153-158
Bolwijn, P.T. & T. Kumpe
1989 "Manufacturing Industries in the nineties." Paper presented at the '2nd International Production Management Conference', Fontainebleau, March.
Bolwijn, P.T. et al.
1988 Flexible Manufacturing. Amsterdam: Elsevier.
Bonney, M.C. & M.A. Head
1992 "Progress on developing a framework for Computer Aided Production Management." Paper presented at '7th International Working seminar on production Economics', Igls, February.
Bossert, James L.
1991 "QFD: a practitioner's approach." New York: Marcel Dekker.
Breun F. & Wohnig W.
1991 "Blechumformwerkzeuge fuer begrenzte Stueckzahlen." (in German), VDI-Z, 1: 77-81
Burstein, Michael C.
1988 "Life-Cycle Costing." In Cost Accounting for the 90's: Responding to the Technological Challenge. Montvale: National Association of Accountants.
Buzacott, J.
1989 "A framework for understanding flexibility of manufacturing systems." Journal of Manufacturing Syetems, 8, 2: 89-96.

Checkland, Peter
1981 Systems Thinking, Systems Practice. New York: Wiley & Sons.
Cheung Y. & Dowd A.
1988 "AI in process planning." CAE Journal, august: 153-156

Clausing, Don and Stuart Pugh
1991 "Enhanced Quality Function Deployment." Paper presented at: Design Productivity International Conference, Honolulu.
Clausing, Don
1991 "Concurrent Engineering." Paper presented at: Design Productivity International Conference, Honolulu.

van Dam, C.
1991 "Vijftig jaar Bedrijfskunde: 1965-2015." (in Dutch) Bedrijfskunde, 63, 1: 4-11.
DIN8580
1985 "Deutsche Industrie Normen." (in German) Darmstadt: Deutsches Institut fuer Normung.
Dirne, C.W.G.M.
1990 Production Control for Flexible Automated Manufacturing Stations in Low Volume Component Manufacturing. PhD thesis, Eindhoven: Eindhoven University of Technology.
Downey, Kirk H., and John W. Slocum
1975 "Uncertainty: Measures, Research, and Sources of Variation." Academy of Management Journal, 18, 3: 562-578
Durlinger, P. & J.C. Wortmann
1983 "KANBAN kan in Japan, maar hier?" (in Dutch) Bedrijfsvoering, 32, 4: 144-147.

Ehrlenspiel, K.
1991 "Integrierte Produkterstellung - Organisation, Methoden, Mittel." (in German) In: J. Milberg, (ed.) Wettbewerbsfaktor Zeit in Produktionsunternehmen: 113-132. Muenchen: Springer Verlag.
El-Gizawy, A.S., J.-Y. Hwang and D.H. Brewer
1989 "A strategy for Concurrent Product and Porcess Design of Aerospace Components." 143-151, In Chao, N.-H. and S. C.-Y. Lu (eds.), Concurrent Product and Process Design: 143-151. New York: ASME.
Enters J. et al.
1990 Kwaliteit en Ontwerp. (in Dutch) Deventer: Kluwer.
Erve H. van 't
1988 Generative CAPP for parts manufacturing. PhD. Thesis, Enschede: Twente University
Eversheim W. et al.
1985 "Design System.", In Design and Synthesis: 189-196, Amsterdam: Elsevier North Holland
Eversheim V., G. Marczinski and R. Cremer
1991 "Structured Modelling of Manufacturing Processes as NC data representation." Annals of the CIRP, 40, 1: 429-32.

Florusse, Leendert B.
1992 "Manufacturing Processes from an Industrial Management Viewpoint." CIM Systems and Advanced Manufacturing Engineering, 5, 4: 269-275.
Florusse, Leendert B. & Don P. Clausing
1992 "A detailed framework for QFD Phase 3." Working Paper, Cambridge: MIT Laboratory for Manufacturing and Productivity.
Fox, R.E.
1984 "MRP, KANBAN or OPT - What's best?" Inventories and production, July/August.

Gadh, R. et al.
1989 "Knowledge Driven Manufacturability Analysis from Feature-Based Representations." In Chao, N.-H. and S. C.-Y. Lu (eds.), Concurrent Product and Process Design: 21-34, New York: ASME.
Galbraith, J.R.
1973 Designing Complex Organizations. Englewood Cliffs: Addison- Wesley.
Garvin D.
1988 Managing Quality. New York: the Free Press.
Georgescu-Roegen, Nicolas
1974 The entropy Law and the Economic Process. Cambridge: Harvard University Press.

Gerwin, Donald

1981 "Relationships between structure and technology." In P.Nystrom and W.Starbuck (eds.), Handbook of Organization Design: 3-38. Cambridge: Cambridge University Press.

Goldratt, E.M. & J.Cox

1986 The Goal. New York: North River Press.

Goswami P.

1973 Beitraege zur Systematisierung der Arbeitsvorbereitung. (in German) PhD Thesis, Zuerich: ETH

Grabowski H. & Seiler W.

1985 "Techniques, Operations and models for functional and Preliminary Design Phases." In Design and Synthesis: 17-22, Amsterdam: Elsevier North Holland

Gupta, Tarun and Biman K. Ghosh

1988 "A survey of Expert Systems in Manufacturing and Process Planning." Computers in Industry, 11: 195-204.

Hage & Aiken

1969 "Routine technology, social structure and organizational goals." Administrative Science Quarterly, 14: 366-376

Hancock, Walton M. et al.

1983 "Assessment of Technologies and Their Utilization." In S.Seashore et al. (eds.), Assessing Organizational Change: 257-284. New York: Wiley & Sons

Harrington, Joseph

1985 Understanding the Manufacturing Process. New York: Marcel Dekker

Hauser, John R. and Don P. Clausing

1988 "The House of Quality." Harvard Business Review, May-June: 63-73.

Hayes, C.C., S. Desa, and P.K. Wright

1989 "Using Process Planning Knowledge to Make Design Suggestions Concurrently." In Chao, N.-H. and S. C.-Y. Lu (eds.), Concurrent Product and Process Design: 87-92. New York: ASME.

Hazlehurst, R.

1969 "A comparison of skills of machinists on NC and Conventional Machines." Journal of Occupational Psychology, 43: 169-182.

Hebbeler M.

1989 Standardisierung von Ablauf- und Zeitplanung. (in German) Koeln: TüV Rheinland

Hoevenaars, A.M.

1991 Produktiestructuur en organisatievernieuwing. (in Dutch) PhD thesis, Eindhoven: Eindhoven University of Technology.

Hofner H.

1969 Verfahren der Umformtechnik. Muenchen: Hanser Verlag

Houten, F.J.A.M. van

1991 PART: a CAPP system. PhD. thesis, Enschede: Twente University.

Hubka V.

1984 Theorie technischer Systeme. (in German) Berlin: Springer Verlag

Hummel, K.E. and C.W. Brown

1989 "The role of features in the implementation of Concurrent Product and Process Design." In Chao, N.-H. and S. C.-Y. Lu (eds.), Concurrent Product and Process Design: 1-8. New York: ASME.

Kalpakjian, Serope

1987 Manufacturing Processes for Engineering Materials. London: Addison-Wesley.

Kals, J.A.G. & L. Houtackers

1988 Omvormende bewerkingen, Omvormwerktuigen. (in Dutch) Lecture notes no. 4511, Eindhoven: Eindhoven University of Technology

Kaplan, Robert S.

1991 "New Systems for Measurement and Control." Engineering Economist, 36, 3: 201-218.

Kargas A., P.Cooley & T. Richards

1988 "Interpretation of engineering drawings as solid models." CAE Journal, April: 67-78.

Kienzle, Otto

1963 "Plastic Deformation Processes." Machine design, November: 200-211.

Krabbendam, J.J.
1991 "Bedrijfskunde in Twente." (in Dutch) Bedrijfskunde, 63, 1: 31-35.
Krause, F.
1989 "A generic approach for modelling in CIM." In Sata, Toshio (ed.), Organization of Engineering Knowledge for Product Modelling in CIM. Amsterdam: Elsevier.
Kudo, H.
1980 "An Attempt for Classification of Metal Forming Operations." Annals of the CIRP, 29, 2: 469-476.
Kumpe T. & Bolwijn P.
1990 "Fabrieken met een toekomst." (in Dutch) Informatie, 32, 11: 873-874

Lange K.
1985 Handbook of Metal Forming. New York: McGraw-Hill
Lange K.
1988 Umformtechnik. (in German) Berlin: Springer Verlag
Lawrence, P.R. & J.W. Lorsch
1967 Organization and environment, managing differentiation and integration. Homewood: Irwin.
Loquet A.
1976 Numerieke codes voor de klassificatie. (in Dutch) Brussel: Fabrimetal.
Luttervelt C. van
1989 "On the selection of Manufacturing Methods etc." In Annals of the CIRP, 38, 2: 587-607
Lyman T. (ed.)
1962 Casting Design Handbook. Ohio: ASM.
Lynch, Beverly P.
1974 "An Empirical Assessment of Perrow's Technology Construct." Administrative Science Quarterly, 19: 338-356

Maloney, L.M., K. Ishii and R.A. Miller
1989 "Compatability-based Selection of Forging Machines and Processes." In Chao, N.-H. and S. C.-Y. Lu (eds.), Concurrent Product and Process Design: 161-168. New York: ASME.
Meerkamm, H., K. Finkenwirth & U. Rase
1989 "A computer aided system for production design." In Proceedings of the Institution of Mechanical Engineers Conference on Engineering Design. London: Mechanical Engineering Publications Limited.
Mielnik, Edward M.
1991 Metalworking Engineering and Science. New York: McGraw-Hill
Mitrofanov S.
1960 Wissenschaftliche Grundlagen der Gruppentechnologie. (in German) Berlin: VEB Verlag Technik.
Myers, Carole & Keith Davids
1992 "Tacit Skills at Work." Personnel Management, 24, 2: 45-47.

Noaker P.
1991 "Scrutinizing Surface Measurement." Manufacturing Engineering, April: 47-51
Noble J.& Tanchoco J.
1990 "Concurrent Design and economic Justification in developing a product." IJOPR, 7: 1225-1238.

Orlicky, J.
1975 Material Requirements Planning. New York: McGraw-Hill.

Pahl G. & Beitz W.
1988 Engineering Design. London: the Design Council, (ed. K.Wallace).
Patel R.& McLeod A.
1988 "Engineering feature description in mechanical engineering design." CAE Journal, October: 180-183.

Perrow, Charles
1967 "A Framework for the Comparative Analysis of Organizations." American Sociological Review, 32: 194-208
Pischetsrieder, B.
1991 "Zeitorientierte Ablauforganisation - Anforderungen, Ansatzpunkte, Instrumente."(in German) In J. Milberg (ed.), Wettbewerbsfaktor Zeit in Produktionsunternehmen: 47-64. Muenchen: Springer Verlag.
Pratt M.
1984 "Solid Modeling and the Interface between Design and Manufacture." IEEE CG&A, July: 52-59.

Regterschot, G.
1992 in personal communication.
Reimann B.
1980 "Organization Structure and Technology in Manufacturing: Systems Versus Work Flow Level Perspectives." Academy of Management Journal, 23, 1: 61-77
Riedel J. & Pawar K.
1990 "Product Design and Manufacturing Strategy, Strategic Choice for Simultaneous vs. Sequential Engineering." Paper presented at: 5th Manufacturing Strategy Conference, University of Warwick, June.

Schey J.A.
1988 Introduction to Manufacturing Processes. New York: McGraw-Hill
Schierbeek B.
1988 "Design in Industrial Design Engineering: teaching design at the school of IDE at the TU Delft." European Journal of Engineering Education, 13, 2: 167-175.
Shah, Jami J.
1988 "Feature transformations between application-specific feature spaces." CAE Journal, December: 247-255.
Shah, Jami J. & Mary T. Rogers
1988 "Functional Requirements and Conceptual Design of the Feature-Based Modelling System." CAE Journal, February: 9-15.
Shingo, S.
1982 Toyota production system - an industrial engineering view. Tokyo: Japan Management Association.
Simon, Hermann
1989 "Die Zeit als strategischer Erfolgsfaktor." (in german) Zeitschrift fuer Betriebswirtschaft, 59, 1: 70-93.
Sitter, U. de, et al.
1986 Het flexibele bedrijf. (in Dutch) Deventer: Kluwer.
Son Y. & Park C.
1987 "Economic Measure of Productivity, Quality and Flexibility in FMS's." Journal of Manufacturing Systems, 6, 3: 193-207.
Sondermann Jochen P. & Ralf Leist
1989 "Methodenbausteine fuer eine qualitaetsorientierte Prozessplanung." (in German) Qualitaetstechnik, 34, 12: 656-662.
Spur G.
1989 "Unternehmensfuehrung in der zukuenftigen Industriegesellschaft." (in German) Vortraege des PTK, Berlin: FhG Institut fuer Produktionsanlagen und Konstruktionstechnik
Spur, Guenther
1991 "Rationalisierung Zeitbestimmender Arbeitsprozesse." (in German) In J. Milberg (ed.), Wettbewerbsfaktor Zeit in Produktionsunternehmen: 95-112. Muenchen: Springer Verlag.
Spur G. & Krause F.
1984 CAD Technik. (in German) Muenchen: Hanser Verlag
Studiegids TUE 1991/1992
1991 Internal publication Eindhoven University of Technology. (in Dutch)
Suh, Nam P.
1990 The principles of design. New York: Oxford University Press.

Suri R. & Shimizu M.
1989 "Design for Analysis." Research in Engineering Design, 1: 105-120.

Taguchi, Genichi and Don P. Clausing
1990 "Robust Quality." Harvard Business Review, 1: 65-75.
Taguchi, Genichi, Elsayed A. Elsayed and Thomas C. Hsiang
1989 Quality Engineering in Production Systems. New York: McGraw-Hill.
Thompson, J.D.
1967 Organizations in Action. New York: McGraw-Hill.

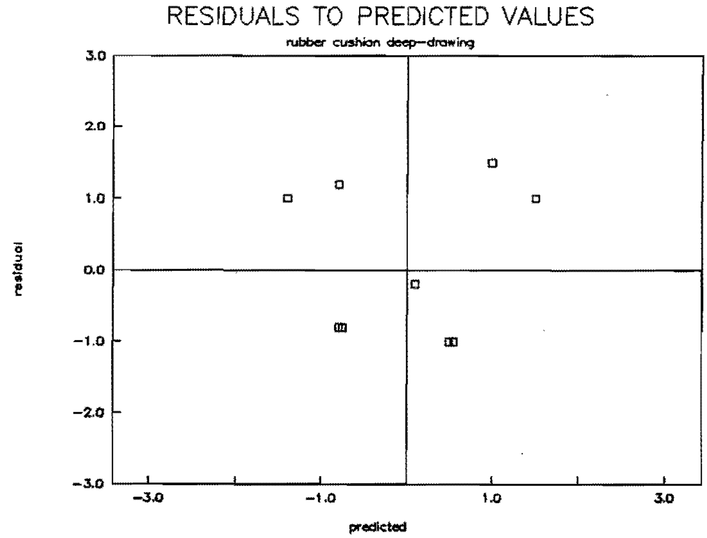
Ullman, David G., Aihua Chen and Brian McGinnis
1990 'Design History, Knowledge Representation and it's basic implementation', working paper DRPG 90-2, Corvallis: Oregon State University, Dept. of Mechanical Engineering
Ullman, David G.
1992 "The Mechanical Design Process." New York: McGraw-Hill.

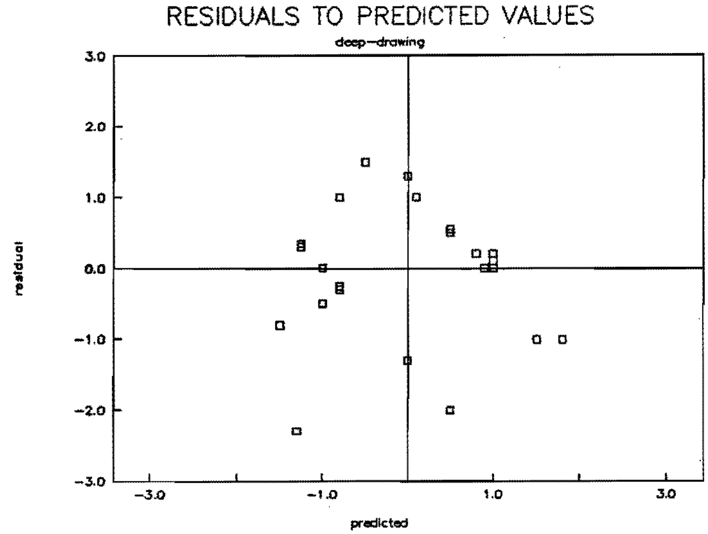
Vancza, Jozsef and Andras Markus
1991 "Genetic Algorithms in process planning." Computers in Industry, 17: 181-194.
Veld, J. in 't
1983 "Analyse van Organisatieproblemen." (in Dutch) Amsterdam: Elsevier.
Van de Ven, Andrew H., Andre L.Delbecq and Richard Koenig
1976 "Determinants of Coordination Modes within Organizations." American Sociological Review, 41: 322-338
Voelcker H.
1988 "Modeling in the Design Process." In Dale Compton W. (ed.), Design and Analysis of Integrated Manufacturing Systems, Washington: National Academy Press: 167-199

Wierda L.
1990 Cost Information Tools for Designers. PhD. Thesis, Delft: Delft University of Technology
Wijngaard, J.
1991 Produktiemanagement, Dan doe ik dit en alles staat stil. (in Dutch) Groningen: Groningen University, Inaugaral Speech.
Williamson I.
1990 "Integrating Design and Manufacturing Strategies for Business Transformation." Paper presented at: 5th Manufacturing Strategy Conference, University of Warwick, June.
Wilson B.
1990 Systems: concepts, methodologies and applications. New York: Wiley and Sons
Wolffgram, H.
1978 Allgemeine Technologie. (in German) Leipzig: VEB.
Woodward, Joan
1958 Management and Technology. London: HSMO.
Woodward J.
1965 Industrial Organization: Theory and Practice. London: Oxford University Press.
Woodward J.
1970 Industrial Organization: Behaviour and Control. London: Oxford University Press.
Woodward, J.A.J. & J. Corbett
1989 "An expert system to assists the design for manufacture of die cast components." In Proceedings of the institution of Mechanical Engineers Conference on Engineering Design. London: Mechanical Engineering Publications Limited.
Wouters, M.J.F.
1992 "Why do managers use sunk capacity costs in decision making?" Paper presented at '7th International Working seminar on production Economics', Igls, February.
Wysk, R.A.
1977 An automated process planning and selection program: APPAS. PhD.Thesis, West Lafayette: Purdue University.

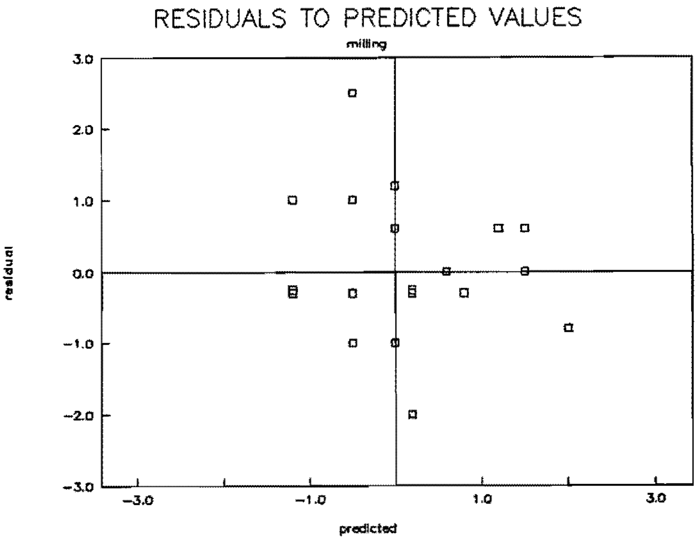
APPENDICES

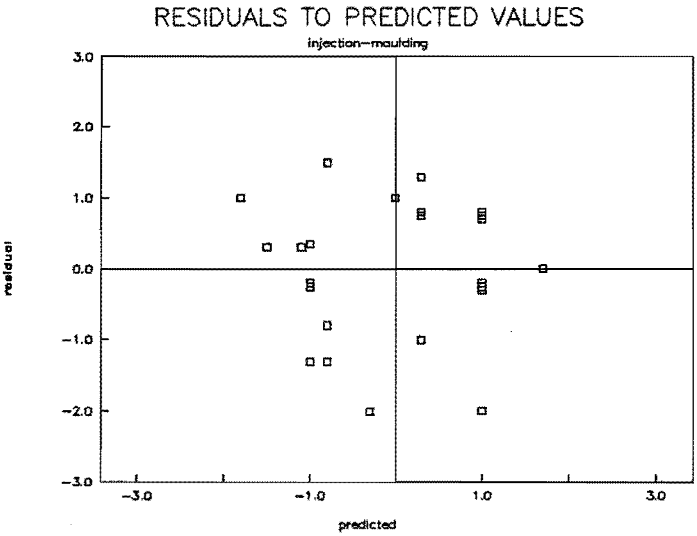
APPENDIX 1





APPENDIX 1 (continued)





APPENDIX 2

DEEP-DRAWING

PC	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0
material	x	x		x	x	x				x	x			x			x			
shape	x	x	x	x	x		x	x	x		x	x		x	x	x	x	x	x	x
surfroughn																				
dimensions	x	x				x				x	x		x	x	x	x	x		x	x
tolerances				x				x										x		

B

PV

1 blank dimensions
2 shape
3 mould positioning
4 material
5 shape
6 dimensions
7 die positioning
8 material
9 shape
10 dimensions
11down-holder material
12 shape
13 dimensions
14 aux.mat. type
15 spot
16 amount
17 energy punch load
18 downholderload
19 rel.move upper start point
20 stop point

Appendix 3. The correlation between the dependent variable and the independent variables for deep-drawing.

	TASKNEW	VERTMOEI	AFHANK	BEHAVAFT
CORRELATION	-.0234	.7113	.2883	*
1-TAILED SIGNIFICANCE	.457	.000	.086	*

* = coefficient can not be computed

Appendix 4. The build-up of the regression model for UNCERPRO for deep-drawing

```
Step number 1.
variable entered: VERTMOEI

Adjusted R²:              .50599
F change   :              22.5
Significance F change:    .0001


Step number 2.
variable entered: AFHANK

Adjusted R²:              .57849
F change   :              3.6
Significance F change:    .0712
```

Appendix 5. The collinearity of the MRA models for the different processes

```
DEEP-DRAWING
Number  Eigenvalue  Cond.Index  variance proportions
                constant  VERTMOEI  AFHANK
1       2.65    1.00  .02   .03     .03
2        .25    3.25  .01   .35     .67
3        .10    5.28  .97   .62     .29

RUBBER-CUSHION DEEP-DRAWING
Number  Eigenvalue  Cond.Index  variance proportions
              constant    VERTMOEI  AFHANK
1     2.79      1.00    .03   .00     .00
2     .19       3.83    .94   .02     .04
3     .02       12.35   .03   .97     .96

INJECTION MOULDING
Number  Eigenvalue  Cond.Index  variance proportions
              constant    VERTMOEI  AFHANK
1     2.87      1.00    .01   .01     .01
2     .10       5.37    .31   .63     .01
3     .03       9.98    .68   .36     .99
```

APPENDIX 6

RUBBER CUSHION DEEP-DRAWING

positive pressing:

PC = B PV

	1	2	3	4	5	6	7	8	9	0
material			x	x	x	x	x	x	x	
shape		x	x	x	x		x	x	x	
surfroughn	x									
dimensions	x		x			x				
tolerances										

1 semi-fin. dimensions
2 shape
3 mat.condition
4 tools material
5 shape
6 dimensions
7 aux. mat. sort
8 location
9 amount
0 energy pressure

negative pressing:

PC = B PV

	1	2	3	4	5	6	7	8	9	0
material		x	x	x	x	x	x	x	x	
shape		x	x	x	x	x	x	x	x	x
surfroughn		x								
dimensions	x		x		x	x				x
tolerances						x				

1 semi-fin. dimensions
2 shape
3 mat.condition
4 tools material
5 shape
6 dimensions
7 aux. mat. sort
8 location
9 amount
0 energy pressure

Appendix 7. The correlation between the dependent variable and the independent variables for rubber-cushion deep-drawing.

	TASKNEW	VERTMOEI	AFHANK	BEHAVAFT
CORRELATION	-.1575	.6207	.7797	.0909
1-TAILED SIGNIFICANCE	.343	.037	.007	.408

Appendix 8. The build-up of the regression model for UNCERPRO for rubber-cushion deep-drawing

Step number 1.
variable entered: VERTMOEI

Adjusted R^2: .29748
F change : 4.38
Significance F change: .0745

Step number 2.
variable enterd: AFHANK

Adjusted R^2: .59465
F change : 6.13
Significance F change: .0480

APPENDIX 9.

DIE CASTING

PC	B																			
	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1
material						x	x	x	x	x	x	x		x				x	x	x	x
shape	x	x	x	x	x	x	x	x	x	x	x		x	x		x	x	x	x	x	x
surfroughness	x	x	x	x		x	x	x	x	x	x	x	x	x		x		x	x	x	
dimensions	x	x	x	x	x	x	x	x	x	x	x		x	x		x					x
tolerances			x		x		x							x			x	x	x		

PV

1 plungerspeed 1st phase
2 switch-over 1st-2nd phase
3 plungerspeed 2nd phase
4 following pressure
5 closing pressure (die)
6 temperature of the melt
7 current/temperature coolingmedium
8 mould: temperature
9 casttree: location
10 casttree: shape
11 casttree: diameter
12 die: material
13 die: shape en diameter deairing
14 die: shape en number cooling channels
15 die: tolerances
16 die: partition
17 die: number of moving parts
18 aux. mat.: amount of discharge fluid
19 aux. mat.: concentration discharge fluid
20 aux. mat.: location discharge fluid
21 open- en close movement die

Appendix 10. The correlation between the dependent variable and the independent variables for die casting.

	TASKNEW	VERTMOEI	AFHANK	BEHAVAFT
CORRELATION	.0443	.7201	.2562	*
1-TAILED SIGNIFICANCE	.419	.000	.113	*

* = coefficient can not be computed

Appendix 11. The build-up of the regression model for UNCERPRO for die casting.

Step number 1.
variable entered: VERTMOEI

Adjusted R^2: .49665
F change : 23.7
Significance F change: .0001

Step number 2.
variable entered: AFHANK

Adjusted R^2: .55640
F change : 4.0
Significance F change: .0597

APPENDIX 12.

MILLING

PC	B									
	1	2	3	4	5	6	7	8	9	0
material	x	x	x		x		x	x	x	x
shape			x		x		x			
surfroughnss	x	x	x		x				x	
dimensions	x	x	x	x	x	x	x		x	
tolerances	x	x	x		x					x

PV

1 spindle speed
2 cutting depth
3 feed: amount
4 feed: direction
5 processing length
6 cutting fluid: spot
7 cutting fluid: amount
8 tool: cutter type
9 tool: diameter
10 tool: material

Appendix 13. The correlation between the dependent variable and the independent variables for milling.

	TASKNEW	VERTMOEI	AFHANK	BEHAVAFT
CORRELATION	.0459	.7067	-.0147	.1689
1-TAILED SIGNIFICANCE	.422	.000	.475	.232

Appendix 14. The build-up of the regression model for UNCERPRO for milli

```
Step number 1.
variable entered: VERTMOEI

Adjusted R2:               .47309
F change    :              18.95
Significance F change:     .0003
```

QUESTIONNAIRE (translated from the original in Dutch)

QUESTIONNAIRE for the INVESTIGATION OF PROCESS PLANNING FOR RUBBER CUSHION DEEP DRAWING

PART:

- the part characteristics:
  name/codenumber: material/thickness:
  shape(features): (sketch)
- processing time (sec.) in production:
- planned yield (%): actual yield (%):
- sudden changes in yield?
- (expected) total production volume:
- production lot-size:
- routing: 1 2

The questions below refer to the determination of process variable values for the part.
The questions should be answered by the employee who actually determined the particular process variable.

1. BLANK:

RESPONDENT - what is your official rank? ..
- how long do you have this job? ..
- what is your formal education? ..

. which part characteristics played a role in the determination of the shape of the blank:
  - the material of the part,
  - (elements of the) shape (features),
  - the tolerances,
  - the surface roughness,
  - dimensions,
  - other ....

. what applies to the determination of the blank shape:
  - I did not have to think very hard, the best shape was obvious
  -
  -
  -
  - I had to think hard, it was not obvious at all what the best shape was

. who did you consult for the determination of the blank shape?
give function/rank/experience:

. how much time did the determination of the blank shape cost?

. was the shape that was determined first, adapted after a first test/production run?

. who was involved in this adaptation?

. how much time did the adaptation cost?

. score the skills that were involved in the task: conceptual and discretionary

2. PRESSURE:

RESPONDENT - what is your official rank? ..
- how long do you have this job? ..
- what is your formal education? ..

If the pressure applied is not the standard 700 bar:
. which part characteristics played a role in the determination of the shaping pressure:
- the material of the part,
- (elements of the) shape (features),
- the tolerances,
- the surface roughness,
- dimensions,
- other ....

. what applies to the determination of the pressure:
- I did not have to think very hard, the best pressure was obvious
-
-
-
- I had to think hard, it was not obvious at all what the best pressure was

. who did you consult for the determination of the pressure?
give function/rank/experience:

. how much time did the determination of the pressure cost?

. was the pressure, that was determined first, adapted after a first test/production run?

. who was involved in this adaptation?

. how much time did the adaptation cost?

. score the skills that were involved in the task: conceptual and discretionary

3. TOOLS:

RESPONDENT: - what is your official function/rank? ..
- how long do you have this job? ..
- what is your formal education? ..

. which tools were used for making this part?

			material		specific	
	y	n	wood	steel	y	n
- mold						
- cover						
- other:						

for non-specific tools:
. what applies to the choice of these tools:
- I did not have to think very hard, the use of these tools was obvious
-
-
-
- I had to think hard, it was not obvious that these tools had to be used

for specific tools:
. which part characteristics played a role in the design of the tools:
- the material of the part,
- (elements of the) shape (features),
- the tolerances,
- the surface roughness,
- dimensions,
- other ....

. what applies to the design of the tools:
- I did not have to think very hard, the shape, material and dimensions where obvious
-
-
-
- I had to think hard, it was not obvious at all what the best design was

. who did you consult for the design
give function/rank/experience:

. how much time did the tool design cost?

. was the design, that came out first, adapted after a first test/production run?

. who was involved in this adaptation?

. how much time did the adaptation cost?

. score the skills that were involved in the task: conceptual and discretionary

4. AUXILIARY MATERIAL: OIL EN RUBBERCUSHIONS

RESPONDENT: FOR THE LUBRICANT - what is your official function/rank? ..
- how long do you have this job? ..
- what is your formal education? ..

. which lubricant was chosen for the making this part? ....

. what applies to the choice of these lubricants:
- I did not have to think very hard, the use of these lubricants was obvious
-
-
-
- I had to think hard, it was not obvious that these lubricants had to be used

. which part characteristics played a role in the choice of these lubricants:
- the material of the part,
- (elements of the) shape (features),
- the tolerances,
- the surface roughness,
- dimensions,
- other ....

. what applies to the choice of the lubricants:
- I did not have to think very hard, the choice was obvious
-
-
-
- I had to think hard, it was not obvious which lubricants had to be applied

. who did you consult for the choice
give function/rank/experience:

. how much time did the choice take?

. was the choice, that came out first, adapted after a first test/production run?

. who was involved in this choice?

. how much time did the choice cost?

. score the skills that were involved in the task: conceptual and discretionary

. can you indicate, per lubricant, precisely where and with how much of this lubricant the part is produced?
Indicate per lubricant:
  - yes, one can indicate precisely where and with how much of this lubricant the part is produced and these spots and quantities are always the same,
  - no, one can not indicate precisely where this part is lubricated and with how much lubricant, this varies from part to part

RESPONDENT: FOR THE RUBBER CUSHIONS: - what is your official function/rank? ..
- how long do you have this job? ..
- what is your formal education? ..

. which rubber cushions were chosen for the making this part? ....

. what applies to the choice of these rubber cushions:
  - I did not have to think very hard, the use of these rubber cushions was obvious
  -
  -
  -
  - I had to think hard, it was not obvious that these rubber cushions had to be used

. which part characteristics played a role in the choice of these rubber cushions:
  - the material of the part,
  - (elements of the) shape (features),
  - the tolerances,
  - the surface roughness,
  - dimensions,
  - other ....

. what applies to the choice of the rubber cushions:
  - I did not have to think very hard, the choice was obvious
  -
  -
  -
  - I had to think hard, it was not obvious which rubber cushions had to be applied

. who did you consult for the choice
give function/rank/experience:

. how much time did the choice take?

. was the choice, that came out first, adapted after a first test/production run?

. who was involved in this choice?

. how much time did the choice cost?

. score the skills that were involved in the task: conceptual and discretionary

. can you indicate, per rubber cushion, precisely where and how the cushion is applied to produce the part?

Indicate per rubber cushion:

- yes, one can indicate precisely where and with how this rubber cushion is applied to produce the part these positions are always the same,
- no, one can not indicate precisely where the cushions are applied, this varies from part to part

About the Author

Leendert B. Florusse was born in Rheden (the Netherlands) on February 19, 1964. After Grammar School he joined the Royal Navy as a midshipman.
In 1988 he graduated at master's level from the Eindhoven University of Technology, School of Industrial Engineering and Management Science. During his study he was actively involved in diverse activities such as the organization of study-tours to Italy and the former Soviet-Union.
In 1988 he joined the Graduate School of Industrial Engineering and Management Science of the Eindhoven University of Technology as a research assistant. This thesis reports on the PhD. project that he carried out in this capacity. During the summer of 1992 Leendert Florusse was visiting scholar at the Massachusetts Institute of Technology (Laboratory for Manufacturing and Productivity) where he worked under the supervision of prof. Don P. Clausing. In the framework of the project he published in Bedrijfskunde, M&O, The International Journal of Production Economics and in CIM Systems and Advanced Manufacturing Engineering and presented papers on conferences in Europe and the USA.

Stellingen

behorende bij het proefschrift

Managerial Manufacturing Technology

door

Leendert Berend Florusse

1. Onderzoek in de Technische Bedrijfskunde dient zich te richten op instrumenten, vaardigheden, organisatie en communicatie voor plannings- en beheersingsactiviteiten dicht bij het primaire proces. De mens dient van het beschouwde systeem een integraal onderdeel uit te maken. De (impliciete) doelstelling van onderzoek dient hierbij te zijn de verbetering van de integrale prestatie van het systeem. (Hoofdstuk 1 van dit proefschrift)

2. De beheersing van de ontwerp en ontwikkelactiviteiten in productiebedrijven wordt een steeds belangrijker veld van bedrijfskundig onderzoek. (Hoofdstuk 2 van dit proefschrift)

3. Het beschouwen van productietechniek in de bedrijfskunde dient zich niet te richten op een product als zodanig maar op een product als vervulling van een vraag/functie en dient zich niet te richten op één machine of proces maar op reeksen van processen/machines die vergelijkbaar zijn omdat ze vanuit vergelijkbare uitgangsmaterialen leiden tot hetzelfde product. (Hoofdstuk 3 van dit proefschrift)

4. De onderlinge afhankelijkheid van procesvariabelen en de meetschaal van procesvaraiabelen en werkstukkenmerken zijn bedrijfskundige aspecten van (mechanische) bewerkingsprocessen. (Hoofdstuk 5 van dit proefschrift)

5. De invloed van de machinekeuze op de taakonzekerheid in de werkvoorbereiding is afhankelijk van het in de productie gehanteerde besturingsconcept. (Hoofdstuk 6 van dit proefschrift)

6. Het begrip 'taakonzekerheid' in combinatie met het besturingsmodel kan worden gezien als een standaard instrument in technisch bedrijfskundig onderzoek.

7. De integratie van het manufacturing features concept in de methode Quality Function Deployment zou aanzienlijk bijdragen tot de praktische toepasbaarheid van QFD.

8. Vakmanschap is het beheersen van niet-kwantificeerbare relaties.

9. In het licht van het beheersen van het productontwikkeltraject is het raadzaam om in de aanloopfase van een product bewerkingsprocessen te gebruiken waarvoor gemakkelijk onafhankelijke manufacturing features kunnen worden gedefiniëerd en die geen specifiek gereedschap vragen. Voor latere levensfasen kan mogelijk worden overgestapt op processen waarvoor dit niet geldt. Dit maakt het mogelijk de, in het algemeen hoge, productiesnelheid van de processen uit de tweede categorie te benutten zonder de nadelen van een moeilijk beheersbaar ontwikkelproces. Aanpassing van het productontwerp zal daarbij nodig zijn.

10. Menswetenschappen, met name betreffende beslisgedrag, behoren tot de kern van de Technische Bedrijfskunde.

11. Het valt in het algemeen niet aan te raden om niet-gepromoveerden bij de begeleiding van een promovendus te betrekken.

12. De titel 'professor' dient uitsluitend te worden toegekend aan voor tenminste 0,8 aangestelden.

13. Een faculteit die begint na te denken over de markt voor haar afgestudeerden is bezig haar academische status te verliezen.

14. Het bedanken van de partner in het voorwoord van een proefschrift duidt op onvoldoende emancipatie van de promovendus.

15. De val van de Berlijnse muur was een trieste gebeurtenis. Het was immers een bewijs voor het onvermogen van mensen om niet in het eigen belang te handelen.

16. De 'algemene' stellingen bij een proefschrift dienen niet serieuzer te worden genomen dan de opmerkingen van een gemiddeld krantelezer.