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PRODUCTION SYSTEM DESIGN AND EVALUATION FOR INCREASED SYSTEM ROBUSTNESS

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ABSTRACT

Effective and robust production systems are required in the competitive environment of today's manufacturing companies. Creating system robustness should be made during the design phase and not during operation when most system parameters already are set. Each production system is the result of a unique and context dependent development process, and its comprising design and evaluation activities are most vital for system performance. The full-text paper is based upon results from more than ten years of theoretical and empirical research studies in the field of production system design and evaluation and lately also in the

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field of robust production systems concerning e.g. manufacturing efficiency and disturbance handling. Industrial examples of how production systems are designed and evaluated will be shown, and its consequences discussed in terms of system robustness and performance in a life-cycle perspective. Issues of importance are e.g. the use of systematic procedures and methods and decisions concerning personal competence and learning strategies.

Keywords: system robustness, manufacturing efficiency, manufacturing, production system design, evaluation

1 INTRODUCTION

The business environment where companies compete has undergone a tremendous change during the past decades. Many companies are competitors in a global marketplace, bringing new possibilities but also new requirements. The continuously increasing market globalisation has many consequences for the manufacturing companies. It affects company ownership and management, the selection of geographical locations of the manufacturing plants, and brings about changing forms for supplier co-operation. In general, companies face the competition on the global market on several levels. The competition not only regards the competitors' products, but also corporate and management strategies as well as production philosophies and processes.

In the past, it has been considered impossible to compete with more than one competitive advantage at a time. The customers of today, however, demand more than low price, for example: they want the best products at the best price with immediate availability (Jackson, 2000). In order to remain competitive, it is essential to provide manufacturing systems able to handle the increased requirements in an adequate way. Proper adjustments to changed requirements and effective use of available resources within the production system are some

of the necessary abilities for maintaining high operations performance, i.e. efficiency and effectiveness of operations, in the rapidly changing business environment (Slack et al., 1998). To be prepared for the different and changeable manufacturing conditions the production systems must be developed with inherent robustness, since robustness is:

”the condition of a product or process design that remains relatively stable with a minimum of variation even though factors that influence operations or usage, such as environment and wear, are constantly changing” (APICS dictionary, 1998)

A robust production system is a stable system which can handle planned as well as unplanned changes. Robustness also facilitates cloning (Grant and Gregory, 1997). That is to move systems without modifications between production sites which is quite common in today’s global market- and production place. To achieve robust production systems, one way is to use Taguchi methods (Chen and Chen, 1996). Robust design methodology (RDM) involves product as well as process design. However, a majority of the examples shown in the literature concerns product design, and not process design. This, together with an awareness of that it is during the design of the production system that the production system capability to a large extent is determined (Bennett and Forrester, 1993; Klein, 1994), motivates further research into how the design and evaluation process can support production system robustness.

2 METHOD AND MATERIAL

The research presented in this paper is based upon theoretical and empirical studies of the system design and evaluation problem of production systems, emphasizing mainly the assembly system before the parts manufacturing system. Concerning the issue of system evaluation,

the empirical material consists of a descriptive and explorative survey within fifteen manufacturing companies in Sweden reported in e.g. Säfsten and Aresu (2000) and Säfsten and Aresu (2002). Moreover results from three case studies are included (Säfsten, 2002). The companies varied in size, from 90 to 2100 employees. Most of the studies were carried out in retrospect. The methods used for data collection during the research studies at the companies were interviews, analysis of internal documents, and observations. The interviews were semi-structured and open-ended, and the respondents mainly consisted of personnel on production management level. The internal documentation consisted of requirement specifications, documented evaluations and evaluation results. The observations can be classified as direct and contextual, according to Yin (1994). The analysis of the data mainly followed the process suggested by Miles and Huberman (1994) for analysis of qualitative data.

The area of production system design was studied empirically in a number of manufacturing companies from 1991 to 1997, presented in short in Bellgran (1998), referring to full reports of each study, respectively. The empirical studies performed in the area of production system design were; a retrospective study of ten Swedish manufacturing companies, a survey investigating the production situation of the suppliers, and six extensive case studies in manufacturing companies. Most of the companies were of medium size, manufacturing mechanical products. The data collection techniques varied depending on type of study. The retrospective study at ten companies was performed through interviews with open-ended questions and observations, the survey comprised a pre-designed questionnaire with fixed/open answer alternatives, and the case studies were performed by the means of interviews, observations and documentation studies.

Lately, research in the area of production system design has been applied on questions concerning production efficiency and effectiveness with focus on disturbance handling from a strategic point of view. This has been made in a national multi-disciplinary co-operation

research project called “TIME” (2001-2004) with researchers from three universities and one institute, see research results in e.g. (Bellgran et al, 2002 and 2003).

3 PRODUCTION SYSTEM DESIGN

System design can be defined as the conception and planning of the overall set of elements and events constituting a system, together with the rules for their relationships in time and space (CIRP, 1990). The term *design* tends to be associated with systems, whereas *planning* tends to focus on processes (Dandy, 1989). Here, design of production systems involves defining the problems, objectives and outlining the alternative course of action (problem-solving), and the evaluation, choices among alternatives and detailed design of proposed production systems (decision-making). The result of the design work is a description (specification) of the production system. Along with the definition of the product development process, the term *production system development* comprises both the design and the realisation of the production system (Bellgran, 1998).

There are mainly two approaches towards a suitable production system. First, planning and control of the existing production system, and second, designing a ‘new’ system. Planning and control of a production system are concerned with operating the resources on a day-to-day basis, and the physical design provides the more or less ‘fixed’ resources that are capable of satisfying the customers’ demands (Slack et al., 1998). Planning and control systems are important, but the possible achievement is restricted by the systems’ inherent characteristics. It is in the design of the system that the constraints in the transformation system can be eliminated (Bennett and Forrester, 1993).

“Whenever a piece of equipment or a system is being designed, the consequences are also, explicitly or implicitly, being designed. If the conse-

quences are to be taken seriously, then the time to take account of them is at the design stage.” (Klein, 1994, p. 208)

3.1 The design process

Based on the core activities and the manufacturing concept selected by each company, certain philosophies and strategies can be determined. These are basic in order to determine the requirements of the specific production system. The system designers, which means those concretely and extensively involved in the production system design process (separated from the term ”designers”, which often refers to product designers) are involved in the design process. The system designers select among the available and identified options in order to create the system alternative that best suits the requirements that have been specified. The production system becomes the result of implementing the ideas that are created and specified in the system design process.

The empirical findings have shown the importance of separating the design process from its planning in terms of how it’s managed and structured. The design process could also be further divided into the preparatory design (where the preconditions are analysed and the requirements are specified) and design specification (dealing with the actual creation and selection of the proposal). A developed model of the production system design task, applied on assembly systems comprises the three parts illustrated in figure 1, each part including relevant aspects on another level of detail, see further in (Bellgran, 1998).

Analysis Model for Assembly System Design

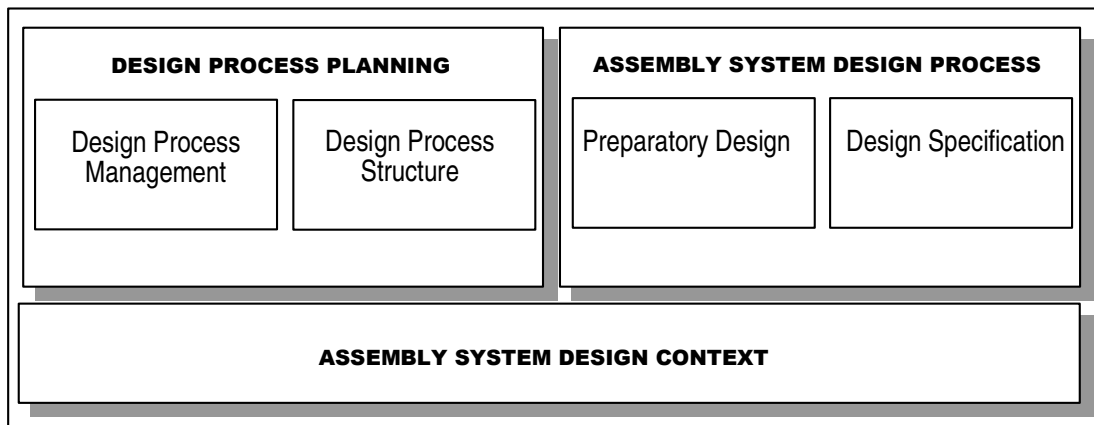


Figure 1 The model illustrates the design process planning, the system design process and the fundamental contextual part (Bellgran, 1998).

In the production system design process, the objective is to design the best possible production system starting from the existing preconditions and the resources and options available. During the system design process, the selection of options is made on the following levels:

- On a system conceptual level (selecting production principle, automation degree, principle for material and product flow, type of work organisation etc).
- On a system detailed level (selecting suppliers, equipment, job design etc.).

The determination of the physical features during the system design process controls the qualities of the production system. However, also other aspects are affected by what happens during the design process. Such aspects are, for example, the time it takes to design and build the production system which in turn controls production start, total time-to-market of the product, and development costs.

3.2 Improvement versus new design

The design process can result in more or less ‘new’ production systems. The extent of the changes varies from being incremental, such as a modification of an existing system, to major shifts in the production principles realised through a new production system design. Depending on the extent of the change, different terminology for the altered production system is appropriate. Almgren (1999) gives the following descriptions of existing, modified and new production systems, see Table 1.

Table 1 New, modified and existing production systems (Almgren, 1999)

Production system characteristics	
Existing	<ul style="list-style-type: none"> • No changes made
Modified	<ul style="list-style-type: none"> • A system that has undergone some technical redesign • A minor change in comparison with a new system
New	<ul style="list-style-type: none"> • Major technical redesign (new machinery and equipment, new layout and flows) and new or modified supplier structure • The organisational dimensions are related to the changes in the technical system • A new industrial facility without previous experience of manufacturing

Referring to the result of a process, a distinction between original design and improvement of existing design can be made saying that the way in which goals are determined in these processes are different (Suh, 1990). In original design (creating a new system), goals are determined in a solution-neutral environment unbiased by preconceived solutions, whereas

improvement of a system means having goals reflecting the existing design (ibid). Changing a production system can imply that something within the existing system is altered to meet the new requirements, or that a new system is designed which is similar or different to the previous one. Van Gigch (1991) considers system improvement to be a transformation or change that brings a system closer to standard or to normal operating conditions set by the original design. Improvement is concerned with introspection, moving inwards the system. System design, on the other hand, is a creative process, questioning the existing solutions, and is concerned with extrospection, moving outwards from the system (Van Gigch, 1991).

Either designing a new production system or improving an existing one, the goal must be to create a robust system able to cope with changing conditions. The proactive approach is necessary, eliminating or preventing possible reasons for disturbances during different life-cycle phases.

3.3 Industrial and academic perspectives on system design

The appearance of the design process differs. A distinction can be made between the academic and the industrial perspectives on production system design (Chryssolouris, 1992), see Table 2. With the academic perspective the problem is often decomposed into manageable sub-problems, such as the resource requirements problem, the resource layout problem, the material flow problem or the buffer capacity problem (Chryssolouris, 1992). This perspective is also recognised as partial theories of production system design (Ruffini, 1999). Apart from the partial theories, there are holistic theories taking a broader approach to production system design. In operations management, 'Design frameworks and strategies' and 'Philosophies with sets of techniques and methods' are mentioned as holistic theories of production system design (Ruffini, 1999).

Table 2 Different perspectives and theories on system design, based on (Ruffini, 1999; Chryssolouris, 1992; Duda, 2000)

Industrial perspective	Academic perspective	
	<i>Partial theories</i>	<i>Holistic (integrated) theories</i>
Trial and error	<ul style="list-style-type: none"> • The resource allocation problem • The resource layout problem • The material flow problem • The buffer capacity problem 	<ul style="list-style-type: none"> • Design frameworks and strategies (e.g. manufacturing strategy) • Philosophies with sets of techniques and methods (e.g. JIT, CIM, TPM) • Design by philosophy (e.g. TPS) • Systems engineering

‘Design frameworks and strategies’ involve Manufacturing strategy, which, however, lacks a methodology for choosing between decision alternatives and does not lead to detailed designs. The other set of holistic theories in operations management is ‘Philosophies with sets of techniques and methods’. The techniques and methods support different philosophies. As an example, Just-in-Time (JIT) is mentioned. JIT is not a design theory in a traditional sense, but rather a set of techniques and methods that support the ability to produce the right product in the right amount on time (Ruffini, 1999). Other examples of theories belonging to ‘Philosophies with sets of techniques and methods’ mentioned by Ruffini (1999) are

Scientific management, Computer Integrated Manufacturing (CIM) and Total Productive Maintenance (TPM).

Similar to the 'Philosophies with sets of techniques and methods', Duda (2000) describes 'Design by philosophy' as an integrated approach to production system design. 'Design by philosophy' is based on a high-level general philosophy of what constitutes a good production system (Duda, 2000). One example of philosophy guiding system designers is the Toyota Production System (TPS). The Toyota Production System is frequently described and discussed in the literature (e.g. Ohno, 1988; Womack *et al.*, 1990; Monden, 1998). Duda (2000) also mentions systems engineering as an integrated approach to production system design. Systems engineering is a top-down design approach aimed at creating products, systems, and structures that will be cost-effective and competitive, taking a life cycle perspective (Blanchard and Fabrycky, 1998).

4 INDUSTRIAL APPROACHES TO PRODUCTION SYSTEM DESIGN

4.1 Industry designing production systems

The empirical findings referred to in (Bellgran, 1998) and presented in e.g. (Bellgran, 2000) focusing on production system design, and assembly systems in specific, indicated that the product design and the production volume had the largest impact on the system. The survey of the assembly situation within 16 Swedish vehicle suppliers indicated that the assembly systems were selected based on requirements of high product quality, flexibility, short set-up times and low costs. Also other factors could be found to have an impact, although many factors seemed to influence the system indirectly by means of its design process. The system design procedures varied depending on each company's specific prerequisites, as noticed in e.g. the study of ten Swedish manufacturing companies. However, many

similarities between their design processes could also be identified. A detailed specification of the requirements was made only in a few cases, and mainly when rather expensive assembly equipment was bought. The layout was often the foundation for discussions and for the creation of different solutions. The most common design procedure was to develop a few alternatives and then rather quickly choose one alternative which was developed further. The chosen alternative was usually selected through discussions in the design team and sometimes with involved operators and, when available, by comparing the alternatives with respect to the requirements fulfilment. No holistic and systematic evaluation of the assembly system alternatives was made at the ten companies. The proposals were not simulated, but most companies used the layout and paper models to test them. The design process could, however, not be considered as being very structured, and no formal methods to support the design processes were available or used by the system designers.

As the interview study was retrospective, it could be noticed that the system designers sometimes had difficulty in recalling how the system design process was performed. This could not be explained solely by the fact that, sometimes, a couple of years had passed since the assembly system was designed. Another reason found was that the system design process was seldom emphasised as a means for reaching the best possible production system. When this lack of emphasis was present, the design process was not structured either (using e.g. a method for the purpose). Consequently, the possibility of recalling how the production system was designed was not facilitated by any pre-defined structure. Possible reasons why the system design process was not focused concerned factors related to attitudes, resources and system view of those involved in the design process.

One reason for not utilizing the system design process better as indicated by the empirical findings was that the design process was not carefully planned before it was initiated. Systematic design would have required a design process structure to follow, and such a

structure was seldom or never identified or determined beforehand, at least not consciously. Some kind of informal structure might have existed, although it was not emphasised as such by the system designers. However, keeping the design process under review could be considered as a precondition for the systematic design of any system.

In three case studies the intention was, however, to design the assembly system in a systematic way following a procedure or a method when designing, i.e. keeping the design process under review. This was sometimes found rather difficult and could not be fulfilled in two of the cases, although the third company partly followed a specific method during the system design process. The management of the design process was identified as relevant in this respect, especially the appointment of system designers and project leader. In the ten companies studied, the assembly systems were usually designed by two to four employees from the production department. When necessary, the system designers consulted experts from other company departments and in four cases, external involvement was utilised. The system designers' impact on the design process, and as a result, on the assembly system specification was found to be extensive. In two companies, organisational changes were made several times within the project in order to handle the changing preconditions. It was indicated that the direction of how the system design project proceeded became different depending on the selected project leader and system designers. Besides the project organisational aspects, the available resources and project priorities were other important factors to be managed within the system design process.

Interesting to note was that how the production/assembly system was designed was not only a consequence of the available options and how the design process was structured and managed. Many factors that could seem rather diffuse or abstract at first seemed to be of great significance for the work as well. The context for the design task was found to be of great importance, not only for the design process but also for its planning. These contextual aspects

were related to the company and its preconditions, e.g. the company culture, production philosophies and strategic considerations. For example, the status of manufacturing at the company, and the allocation of production engineering resources affected the project resources as well as project priorities. From these empirical findings but also from theoretical studies, a complex pattern of factors or aspects was found to influence or control how the assembly systems were designed (Bellgran, 1998 and 2000). The model presented in figure 1 describes the principles of these findings.

4.2 Concept-driven and concept-generating approaches

Other empirical findings also showed that the approaches of being either *concept-generating* or *concept-driven* influenced the design processes within the companies (Säfsten, 2002). From the perspective of the studied companies, a third design approach appeared, reflecting the situation when the design of the production system, or part of the design, was handed over to production system suppliers. The production system suppliers suggested possible alternatives based on more or less detailed requirements specifications and a third approach emerged: the *supplier-driven* approach.

When the design process is driven by something external; for example, a pre-existing design or the interests of an actor, the process is *concept-driven* (Engström *et al.*, 1998). A constraint-driven design process is described as following an internal logic, starting with an analysis of the requirements and the specific situation and working towards the solution. When the design is guided by a number of constraints (requirements), such as the type of product, volume and number of variants the design options are successively eliminated through irreversible design decisions resulting in new constraints, until only one alternative remains. The result of the constraint-driven approach is that a 'new' system solution is generated; a *concept-generating* approach to the design process is described.

When the *concept-generating* approach was applied, the design process more or less followed the phases prescribed in the general design process, see Figure 2 (A). When the *concept-driven* approach was applied, a preferred production system concept was given from the beginning of the design process and the conceptual design phase was more or less excluded, see Figure 2 (B). The described consequences for the design process from the *concept-generating* and the *concept-driven* approaches presupposed that production system design would be carried out at the manufacturing company.

The supplier-driven approach, see Figure 2 (C), involves different degrees of involvement by the manufacturing companies. From the perspective of the system supplier can the design process be of either a *concept-generating* character or a *concept-driven* character. The system suppliers often use ‘standard’ solutions, which are modified according to the specific situations, i.e. a *concept-driven* approach is often applied.

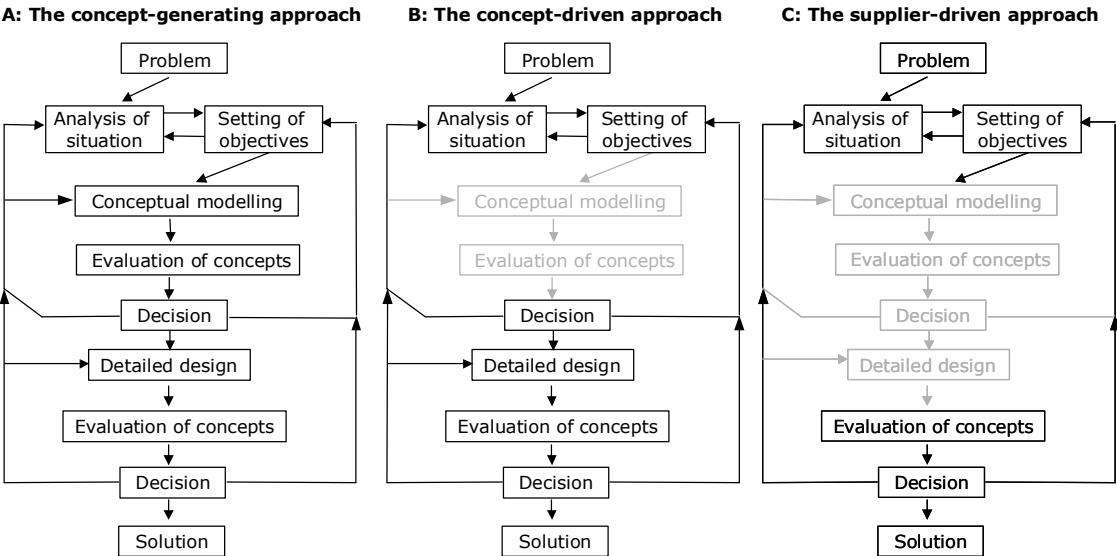


Figure 2 Different approaches to system design from the perspective of the manufacturing company

4.3 Design approaches and evaluation

According to the interpretations made of the design processes carried out within the companies, the different approaches imply differences concerning the activities carried out during the design processes. Consequently, the activities concerning evaluation were also affected.

When the *concept-generating* approach was applied, quite extensive evaluation efforts were described during the design process. On a conceptual level, there was more than one concept to evaluate and the evaluation after implementation was less extensive than during the design process. Several more or less informal evaluations preceded the different decisions made during the design process, and the production system was evaluated along the way. The resulting solution was thereby already accepted. This can be compared with an issue raised by Wu (1994) concerning the superficial treatment of evaluation in several system design models. Wu claimed that the application of a systematic design approach gives a false picture of a correct solution. A systematic design approach as such is *not* a guarantee for appropriate result.

The *concept-driven* approach can be compared to ‘improvement’ while the *concept-generating* approach can be compared to ‘design’ when design aims at producing new solutions. The difference between improvement and design has implications for the evaluation. In improvement, the solution needs to be evaluated against the standard or the normal operating conditions aimed at (goal-based evaluation). In design, the goal might be unclear, and therefore the focus might be on comparing different solutions during the design process (goal-free evaluation).

The *concept-generating* approach and the *concept-driven* approach to design provided two different perspectives of evaluation related to the advocated production principles. When the *concept-driven* approach is applied the question for evaluation are whether the production

system fulfils the advocated principles, and when the *concept-generating* approach is applied, the question is whether the advocated principles are appropriate.

When the *supplier-driven* approach is applied, the system design process is more or less a 'black box' from the perspective of the manufacturing company. According to the empirical findings, the company formulated the objectives and achieved the result (the production system) from the supplier when this approach was applied. Here, the difficulty lies in finding the appropriate relations between the objective and the result. The simple relation problem does not consider the activities actually carried out between the objective and the result.

The *supplier-driven* approach to design typically resulted in several production system solutions, in comparison with the *concept-generating* approach and the *concept-driven* approach, which resulted in one solution. When several solutions are suggested by system suppliers for a manufacturing company, two main perspectives of evaluation are found. The questions are whether the suggested production system fulfils the requirements and whether the production system supplier is reliable, trustworthy, and co-operative.

5 DOWNSTREAM CONSEQUENCES OF A NON-ROBUST SYSTEM DESIGN PROCESS

When the work performed during the system design process is not sufficiently thorough, problems will most likely appear within the physical production system, i.e. we find downstream consequences of a non-robust engineering process. Examples of such problems or deficiencies of the production system are (Bellgran, 1998):

- Implementation problems
- Running-in problems
- Production disturbances
- Maintenance problems

- The work organization does not fit the technical system
- Need for capacity change
- Need for immediate technical and/or work organizational changes

Problems when implementing and running-in the production system increase the development costs and will most likely extend the time-to-market of the products as well. Difficulties related to production and maintenance of the production system reduces productivity, increase product costs and thereby reduces profitability. Also the fact that the work organization does not always fit the technical system is a problem that has impact on the productivity and consequently, on profitability. The difficulty of predicting the future customer demands is indicated by the need to reduce, but more probably, to increase the capacity of the production system. The need for immediate or later technical and work organizational changes within the production system is often a consequence of poorly analyzed preconditions when designing. Production system changes may also become necessary due to late product design changes. The probability of such problems taking place is evident. However, to what extent and why they appear is more difficult to foresee. It is, therefore, relevant to consider future product requirements and changes when designing production systems.

A production system which is perfectly designed from the outset will certainly lead to fewer problems appearing, and will minimize, although not eliminate, the need for changes at a stage when the system is already built. On the other hand, an production system that is imperfectly designed concerning, for example, performance quality, material flow and product flow, can bring about immense costs through high tied-up capital, rejected products, low delivery ability, low reliability etc. Deficiencies and faults in the work of preceding phases such as engineering or design manifest themselves in the start-up of an production system (Wiendahl, 1996).

Besides those possible problems of the production system, we can also find deficiencies in how the system design process is performed. When production systems are not designed in an efficient way, this may cause disadvantages, such as:

- The time for designing the production system is not utilized in an efficient way.
- The design costs consequently become high.
- The outcome, i.e. the production system, is affected.

Delays in relation to original timetables, high costs compared to original investments and budgets, and poorer production system performance than estimated, are typical problems in industry also when designing and implementing any new production system (Johansson, 1996). How the system design process is performed is important for the success of the production system, and its profitability. To emphasise the way production systems are designed, therefore, offers large potential for improvements.

6 ROBUST PRODUCTION SYSTEMS ARE REQUIRED

6.1 Robust design

Continuous improvements, fast and parallel development processes, and reduced set-up times in the production systems are a reality for today's enterprises. It requires production systems to be designed in such a way that internal and external changes as well as disturbances can be handled during operation without losing efficiency, flexibility and speed – and as a consequence profitability (e.g. Corrêa, 1994). Production systems must be robust enough to handle internal and external changes and disturbances. Under the condition that the product design is right, the production system determines not only the final qualities of the products,

but has also a large impact on time-to-market, time-to-customer, delivery precision and product costs.

A methodology for achieving robustness is robust engineering, which optimizes for the robust function (Taguchi et al, 2000). The methodology or strategy is ideally used for the development of new technologies in the areas of product and process design, and it basically:

“Concentrates on identifying the “ideal function” for a specific technology or product/process design”, and “Concentrates on selectively choosing the best nominal values of design parameters that optimize performance reliability (even in the presence of factors causing variability) at lowest cost” (Taguchi et al, 2000 p 2).

Taguchi, the inventor of the Taguchi method that founds the development of robust engineering, makes a definition of robustness that reflects the concept saying robustness is:

“The state where the technology, product, or process performance is minimally sensitive to factors causing variability (either in the manufacturing or user’s environment) and aging at the lowest unit manufacturing cost.”
(Taguchi et al, 2000 p 4).

A robust production system is here defined as a system than can handle both foreseen and unforeseen variations and situations. The robustness of the production system in meeting the dynamic environment can be the difference between success and failure to a manufacturing company. The consequences of a non-robust production system can be low utilization of resources and a disability to handle frequent disturbances. Quality problems and low productivity are consequences that directly affect the profitability of the manufacturing company.

6.2 Achievement of robust production systems

Before approaching the problem of how to achieve a robust production system, a fundamental question concerns how to measure the robustness of a production system? In general terms – and according to Taguchi mainly referring to product design, a measure of robustness that an engineer is required to evaluate is “the signal-to-noise” ratio, particularly if the engineers activities are upstreams in the R & D and advanced engineering phases of design, see (Taguchi et al, 2000). Otherwise, the engineer is forced to evaluate the less efficient, downstream characteristics of quality. Signal-to-noise is here expressed as the ratio of the level of performance of the desired function to the variability of the desired function. The higher the ratio, the higher the quality (ibid). Transferring this thinking to the production system, one way of measuring its robustness is naturally to divide the system into its separate functions, measuring each separate function in terms of robustness. However, with a systems view this approach is less relevant, especially since also the human being is a part of the production system which is not the case when defining a product. The question is still whether and how the robustness of a production system could be measured upstreams, instead of evaluating the downstream effects in later phases.

The ability of a production system to support overall goals of a company is determined by its design. There is no single best solution always supporting certain strategies. The system design needs to correspond to the specific circumstances at each company. Different system designs can result in similar performance which implies that, in order to arrive at an ‘optimal’ design, theories on the design of manufacturing systems should be able to generate and evaluate different designs (Ruffini, 1999). Consequently, the ability to evaluate different design solutions is essential when striving towards a manufacturing system successfully meeting the particular requirements.

Each production system is the result of a unique and context dependent development process. It is, therefore, important to highlight the development process and its comprising activities as important to the production system performance, and thereby the robustness of the production system. The design process comprises preparatory design activities and design specification activities and should be performed in combination with evaluation of the existing production systems, evaluation of proposed production system alternatives, and evaluation of the implemented system in terms of follow-up.

To achieve a robust production system, the system designers need to identify the relevant design variables and decide about the best level of these variables based on a systems approach. Optimizing units separately will lead to a risk for suboptimization, which is not a good precondition for robustness. Opportunities to increase system robustness are also improved if the whole life cycle of systems are taken into account, see figure 3. The single life-cycle phase of production operation, only provides limited possibilities to reduce disturbances (Bellgran et al, 2002). In addition, robust design solutions are much easier to modify (and at a much lower cost) during early phases of production development.

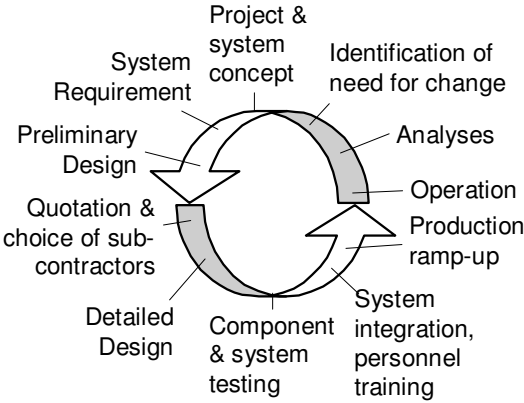


Figure 3. The robustness of a production system should be considered with a life cycle approach on the system (Bellgran et al, 2002).

We can find other design variables of importance to the robustness of a production system. Finding a balance between system flexibility, product generations to be produced, and technology and methods that should be used for implementation are important preconditions as regards production disturbance handling during start-up and volume production (Bellgran et al, 2002). These are questions that should be considered during the system requirement definition and preliminary design phase. The decision between, on one hand: a traditional safe solution, or on the other hand: a new, competitive solution that will survive longer, but are also more risky and more prone to disturbances, is delicate but important as regards system robustness. It is not that easy to determine which solutions are standard off-the-shelf, and which are special designs that may imply more disturbances due to e.g. design deficiencies, component problems, un-sufficient validity and reliability tests etc (Bellgran et al, 2002).

7 STRATEGIES FOR PRODUCTION SYSTEM ROBUSTNESS

7.1 Focus on system robustness – a way to concentrate resources

The need for developing and transferring ordering competence is a factor of importance for the creation of robust production systems. It for example deals with questions during the quotation and choice of sub-contractor (Bellgran et al, 2002). The choice and evaluation of proper subcontractors, the evaluation of best bid, and the agreements and collaboration with them, provide a base for the detailed design phase that may determine much of the future production disturbances (ibid).

Another relevant robustness factor to consider is to build new systems based on knowledge and experience from earlier projects, as we can find many decisions to be taken based on experience (Bellgran et al, 2002). As identified in empirical studies within the TIME project as well as in earlier studies (Bellgran, 1998) a problem is that this knowledge and

experience of (senior) system designers may be difficult to extract and document. The consequence is a company dependency for certain individual's competence. Some of the design knowledge may be documented in for example guidelines or specifications. Some can even be implemented as methods or other types of supportive tools, to be used by less experienced engineers to make proper decisions. However, to a large extent this knowledge is kept within individuals (Bellgran et al, 2002).

7.2 Learning strategies supports a robust thinking

Knowledge of different types appears on different levels during design and evaluation of production systems, i.e. both within individuals and the organization. Only a small part of the knowledge concerning design and evaluation of production systems is internalized in the organization, the majority is internalized by the individuals. A difficulty of transferring individual knowledge to organizational knowledge is empirically identified (Säfsten, 2002; Bellgran, 1998). Concerning design, it is illustrated by the lack of systematization of the design process, i.e. a lack of tools, working methods, and organisational forms. The system designers have not transferred their knowledge to codified knowledge that could be used by others when designing the next system. Concerning evaluation, the same is true, i.e. there is a lack of working principles, tools, methods etc that could support the evaluation process.

The learning process often involves transfer from tacit to tacit knowledge, i.e. *socialization* (Nonaka, 1991). The problem can be related to the three steps of the learning process:

- Experience accumulation (learning by doing, using). Outcome: local experts
- Knowledge articulation (discussion, reflection). Outcome: improved general understanding
- Knowledge codification (writing, implementation). Outcome: manuals, procedures

From a design science perspective, the different kind of knowledge that is needed by the technical experts working with system development tasks could be separated into general knowledge (relating to activities) about designing or planning, manufacturing, production etc. while the more specific knowledge refers to the corresponding real object system (the technical system) on which work is being done (Hubka and Eder, 1996).

Methods, models and other types of supportive tools are means to create and maintain knowledge between and within people being involved in the process of designing robust production systems. One general problem is, however, the limited industrial use of supportive tools during design or change of production systems (Bellgran, 1998; Säfsten, 2002). The existence and use of theoretical models, methods and frameworks are thus not sufficient enough today to improve the production system design situation with the perspective of robustness.

Knowledge could be developed to common performance praxis that is independent of individuals, and applied at different phases of the production system life-cycle, i.e. not only during the creative design phase but also during for example installation and ramp-up of a system. The question is how this knowledge can be made available to other engineers at the company? Specific knowledge on e.g. previous conceptual and detailed technical and work organisational solutions are much valuable, but may be difficult (or found time-consuming) to transfer between projects (Bellgran et al, 2002). Finding ways of making this knowledge transfer is, therefore, of interest. For example, procedures or methods could be developed in order to analyse, identify, and document knowledge and experiences from one project to the next.

A conclusion is that the creation of sustainable knowledge should be considered a relevant factor when improving the preconditions for robust production. The knowledge and experience by those individuals designing and evaluating production systems are central for

their possibility to create robust production systems. It certainly affects the way the task is approached and whether robustness is considered a goal parameter when designing, affecting decisions on both conceptual and detailed technical and organizational level.

8 CONCLUSIONS

In this paper it is argued that robust production systems are a way to handle the ever changing environment for manufacturing companies. The robustness of production systems is important for any manufacturing company's possibility to produce high-quality products on customer demand – and to production costs that creates profitability. Today, too much time is spent on handling disturbances during different life-cycle phases of the production system. Overall equipment efficiency (OEE) is, therefore, mostly low in many manufacturing plants. To be able to compete on the global market, production costs are important as argument for where to locate production. More robust production systems with high availability are, therefore, of utmost importance to those companies that want to stay competitive in manufacturing.

Robustness can be achieved during the design process more easily and to lower costs, than during the operation phase when most system parameters are already set. However, we need to improve strategies for how to develop robust production systems. Preparing for different system generations besides different product generations is one example of how to work strategically towards increasing robustness. Another example on strategic level concerns strategies for how the tolerances, within which a production system may vary, are defined and set initially during the design phase and later during improvements. We need to create models and systems that make it possible to handle variations within these tolerances, and we also need to learn how to handle tolerances others than technical ones. A conscious approach towards developing robust production systems, avoiding the downstream consequences of a

non-robust system design process, and hence, a non-robust production system will certainly improve the profitability of the manufacturing industry as a whole.

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