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ScienceDirect

Procedia Computer Science 28 (2014) 34 – 43

Procedia Computer Science

Conference on Systems Engineering Research (CSER 2014)

Eds.: Azad M. Madni, University of Southern California; Barry Boehm, University of Southern California; Michael Sievers, Jet Propulsion Laboratory; Marilee Wheaton, The Aerospace Corporation
Redondo Beach, CA, March 21-22, 2014

Assessment of Production System Alternatives During Early Development Phase

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Abstract

The development of modern mechatronic systems is characterized by a rising complexity and an increasing necessity to develop product and according production system in a close interplay. Model-based Systems Engineering has been introduced to cope with these challenges by means of an integrated system model. It enables the consideration of possible interdependencies and allows the analysis of the whole system model from the beginning. Especially during the early phase of the production system development many interdependencies have to be considered while the information are still vague and most system specifications yet have to be determined. The objective of the approach presented in this contribution is therefore to compare and assess early alternative production system specifications parallel to the development in order to reduce the relevant solution space and save valuable development resources. For that purpose a three stage evaluation procedure is proposed and methodologically founded. Additionally an according multi criteria structure that is based on common specification languages like CONSENS or SysML is presented and the practicality of the approach is demonstrated with an application example.

Keywords: Model-based Systems Engineering (MBSE), Integrative Production System Development, Production System Assessment, Multi Criteria Decision Support, Analytic Network Process

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1877-0509
doi:10.1016/j.procs.2014.03.005

1. Introduction

Increasingly global competitions as well as decreasing product life cycles force companies to constantly improve their engineering capabilities. To succeed in an agile and highly competitive business environment, it is mandatory to avoid wasting time and money during development through resource-intensive iteration loops. To accomplish this objective, future improvements must not only comprise merely technical optimizations but also a broader perspective on product design and development. In industrial practice the production system development is usually not begun with until the product development is almost finished. However many product design decisions highly affect the production system development and vice versa, so it is more than ever important to consider the relations as early as possible and develop product as well as production system in a close interplay[1]. An example for relevant interdependencies is the material selection during product development that requires certain manufacturing technologies, e.g. aluminum welding. If these capabilities are not available within the company it might be more efficient to select another material during the product development phase[2].

The example illustrates the potentials of an early and integrative development of product and corresponding production system, i.e. starting the production system development as soon as a principle solution of the product has been defined. However the grand challenge of the early development phase is the high amount of incomplete and vague information. Additionally the consideration of all relevant interdependencies between product und production system development comes with the price of an exponentially rising complexity of the engineering task. Since domain-specific engineering methodologies cannot sufficiently handle this complexity, Model-based Systems Engineering (MBSE) has been introduced to solve this challenge[3]. MBSE relies on a general system model that comprises all the required domain-spanning interdependencies and coordinates the involved domain-specific models. The system model structures the relevant information and defines clear interfaces between the subsystems as well as to the environment. Its purpose is not only to serve as a starting point before the domain-specific system development is pursued, but also to act as a common information exchange layer for the involved disciplines throughout the whole product engineering process[4].

Modeling systems according to MBSE principles from the beginning enables a highly efficient system development that requires less iteration loops, thus reducing development time and money spent. Since potential inconsistencies of the development between different domains or subsystems are discovered immediately, the engineers receive a continuous feedback if certain adaptions violate the boundary conditions of other domain-specific systems or decrease the overall performance of the system. This procedure avoids the isolated optimization of independent subsystems that might cause conflicts in the system integration phase of the development process.

The integrative development of product and production system can therefore particularly benefit from the MBSE methodology. Especially early analyses of the integrated system model offer significant potentials to realize a leaner development process. When only a first concept of the product is available, a high degree of freedom results for the according production system development. For this reason the main objective of the production system development during the early design phase is the exclusion of unsuitable processes from the solution space. This enables an evaluation of the most promising production system alternatives so developers can focus on the best solutions right from the beginning. The criteria for the evaluation must be chosen in accordance with the overall objective of the production system development, e.g. flexible, sustainable or low-cost manufacturing. Each overall objective is determined by a multitude of criteria with different importance that are individually assigned depending on the specific planning task. Besides the differences between the criteria's importance the criteria themselves are also different in nature, i.e. quantitative as well as qualitative. Despite these challenges it is necessary to merge all criteria within a unified methodology to achieve an efficient and objective-oriented engineering process.

This contribution proposes an MBSE-based multi-criteria decision support approach for the evaluation of production system alternatives during the early design phase. For that purpose the development of a general system model as well as existing approaches for multi-criteria decision support will be described in more detail in section 2. The approach for the analysis of the general system model with regard to the overall objective is then introduced in section 3, followed by an application example that validates the proposed procedure in section 4. The contribution is finished with a conclusion as well as an outlook to the future research challenges in section 5.

2. Methodological Foundation

In this section the integrative development of product and production system will be described in more detail. To perform this task according to MBSE principles a common specification language is required, for which two possible approaches are presented. Furthermore for the evaluation of specified production system alternatives a multi-criteria decision making method is proposed that can process criteria with very different characteristics.

2.1 Process of integrative production system development

To achieve a close interaction between product development and production system development it is advisable to begin the production system design as soon as a first draft of the product has been defined, i.e. the principle solution. Figure 1 gives an overview of the idealized process sequence and the according development tasks.

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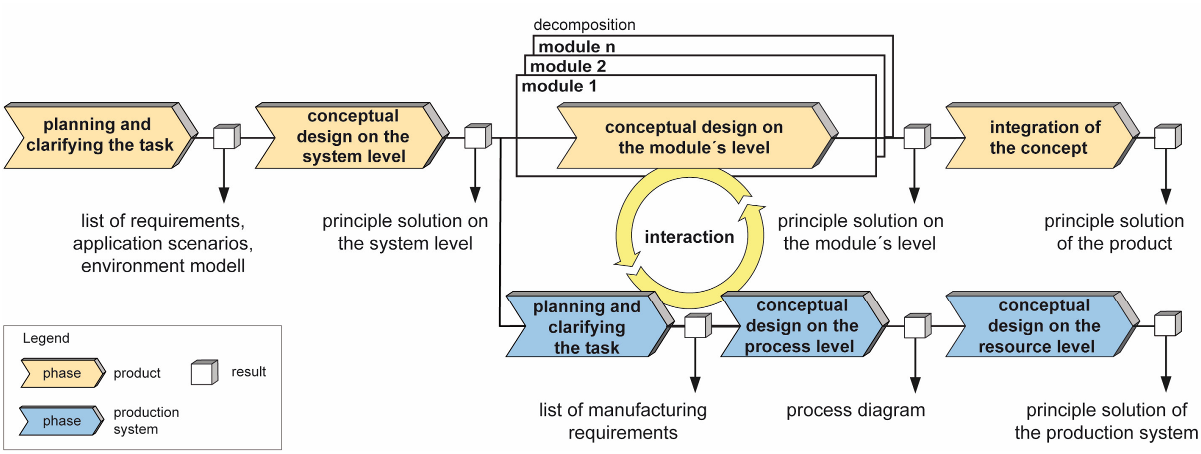

Fig. 1. Sequence of integrative production system development tasks according to Gausemeier et al.[5]

Figure 1 also denotes the interdependencies between the two development branches that have to be considered. Once the common understanding of the system and its interfaces is represented by the conceptual design on the system's level, the subsystems and modules can be developed within the specified parameters[6]. A well-defined system model ensures the consistency between the module- and production system development. The according modelling process should be supported by applying Systems Thinking frameworks as for example the Conceptagon approach[7].

Analysis models for the system then allow for an early assessment of characteristic system parameters, e.g. estimation of costs, performance or robustness. On the one hand these parameters can be evaluated individually, for example by means of spider/radar charts or other geometries[8]. On the other hand it is possible to assess the system holistically, based on a formal system representation. For this purpose the specification of system models with dedicated modelling techniques is mandatory, so two of such approaches will be introduced in the following section.

2.2 Specification of a general system model

To ensure a seamless communication between developers of different subsystems or domains it is necessary to specify the general system model in a common language with defined interfaces to domain-specific languages. For this purpose several specification techniques and languages have been proposed by academia as well as practice, of which SysML and CONSENS will be representatively described here in the following.

Systems Modeling Language (SysML)

The Systems Modeling Language (SysML) has been introduced in 2006 as domain-spanning modeling language for the design and development of complex systems. Its particular purpose is to enable a seamless model-based communication from the setup of system requirements to the development and integration of all subsystems.

SysML is a derivation of the Unified Modeling Language (UML) that is mainly used for the specification of software systems[9]. SysML consists of 4 basic views on the system, of which each contains a certain number of diagrams that allow the specification of particular system characteristics[10]:

1. The structure of the system is modeled by Block Definition Diagrams (bdd) and Internal Block Diagrams (ibd). The bdd represent an abstract high-level view on the system where the main system elements are defined and their functional relations are modeled, e.g. “contains” or “is part of”. The ibd is used to model more detailed properties of the system elements, as for example the type of interfaces and the different flows between them.
2. The behavior of the system is represented in different kinds of behavior diagrams. Sequence diagrams (sd) help to model the temporal course of communication between the system elements. The communication is displayed as an ordered sequence of messages that make it easier to identify cause and effect of a certain behavior. State machines (stm) are used to model all possible states that the system is operating in and the events that make it change the states. The activity diagram (act) fulfills a similar purpose however it depicts more closely what happens during an activity that performs the state change.
3. A continuous tracking of requirements through the development process is one of the main advantages of SysML. It is achieved by specifying a requirements diagram (req), which not only allows deriving sub requirements but also to cross-check which system element or function satisfies which requirement.
4. The parameter diagram (par) is meant to analytically describe functional relations between system elements and their environment. The specification is conducted with mathematical equations that later form the foundation for the analysis of the system behavior, e.g. temperature development during operation or forces while moving.

Through the various diagrams that are offered by SysML it is possible to design a domain-spanning system model that contains most relevant initial information for the later domain-specific system development. SysML is widely accepted among industrial practitioners as well as academic researchers, however the modeling focus is mainly on communication and other flows as well as functional relations. The development of production systems is well supported for the requirements engineering and the product specification. The specification of technological interdependencies between product and corresponding production system is not directly offered by a diagram, although the combination of diagrams offers potentials to solve this task[11]. A more specialized language for the system specification of mechatronic systems will be introduced in the following section.

CONceptual Design Specification Technique for the ENgineering of Complex Systems (CONSENS)

CONSENS has been developed with a specific focus on the integrative development of product and production system where the general system model consists of a system of coherent partial models. Product as well as production system model each have certain partial models assigned that represent specific views or aspects of the system. Due to the several relations between the partial models themselves and also between product and production system it is possible to have a continuous matching of both planning domains[5].

Figure 3 gives an overview of all involved partial models and the way they act together. Based on a first product conception, e.g. specified requirements, active structure, environment model and a rough shape, the production system development can be initiated. Both planning tasks are then performed in a close interplay to iteratively refine the general system model. With regard to the assessment of production systems, the according production system partial models are described in more detail as follows[5]:

1. Production System Requirements specify those requirements that are particularly important for the system manufacturing and assembly. These are for example required annual production rates, manufacturing tolerances or technologies to be used. The information are mainly obtained from the intended business model of the

product that has been set up before the product development. For example, business models that aim for a technology leadership of the product need different production system requirements than business models that aim for the cheapest product in the market. In CONSENS the requirements are simply specified as an ID-based text list where some requirements that are satisfied by a particular system element can be linked to other partial models. It differentiates between compulsory and optional requirements. To specify the general system model special attention must be paid to model the requirements on an appropriate level without too specific aspects. Otherwise the requirements would grow excessively in volume and prevent an efficient Systems Engineering.

2. The Process Sequence can be specified in accordance with a first product shape model as well as the Active Structure. It consists of consecutive processes and material elements that lead from the manufacturing of the basic components to the assembly of the final system. The process sequence is specified independently from the actual resources that will later realize the production process. This resource-independent approach enables a neutral development process that does not favor established solutions during the early development. Processes are only specified with the most important process parameters, thus conserving the potential solution space.

3. Resources must be assigned to every process of the Process Sequence to execute the according task. Every process must have one resource assigned, however one resource can be assigned to multiple processes. Resources are specified by certain production parameters, e.g. processing speed or workspace limitations. Additionally the Resource Diagram can mark a resource as make or buy capability, since some processes must be executed externally. Supporting units that are required for the operation of certain resources as for example workers or tools are also specified within the resource diagram.

4. The Shape of the production system does not only comprise a three dimensional model of the resources but also layout information of the plant and spatial information of the machine positions. It constitutes the basis for later material flow analyses and capacity dimensioning.

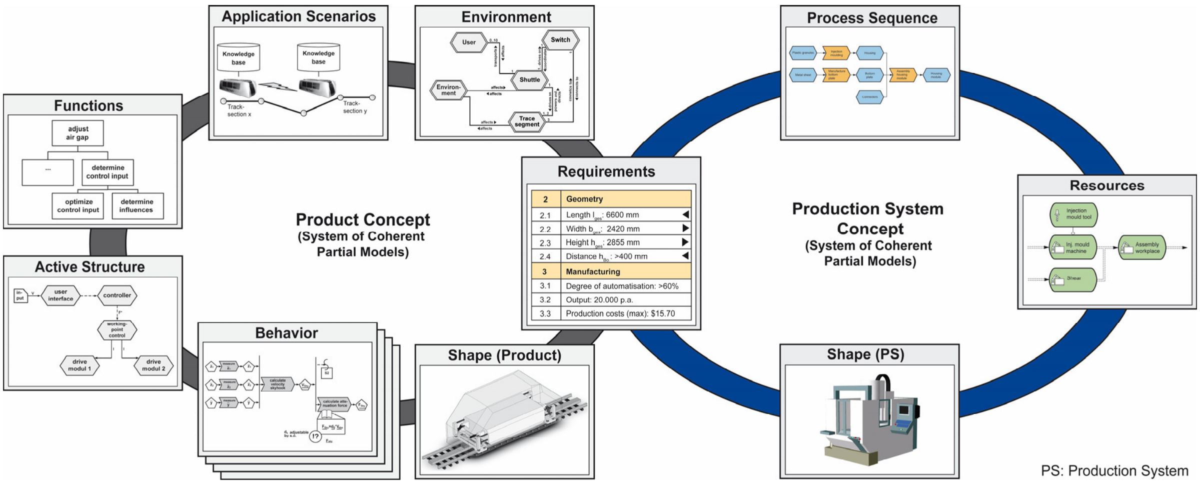

Fig. 2. Partial models of product and production system in CONSENS according to Gausemeier et al.[5]

All described partial models are interlinked with each other to represent the interdependencies between product and production system as well as between the aspects of the system itself. Examples are requirements that are fulfilled by system elements of the Active Structure or processes that are realized by resources which have a certain shape. To compare different production system specifications with each other it is necessary to consider all aspects of the production system together with its interdependencies. Since all the relevant decision criteria exhibit very different characteristics with regard to any evaluation, e.g. quantitative/qualitative measures or linear/exponential behavior, methods of Multi Criteria Decision Support are required for the assessment. In the following section, these methods will be introduced in more detail.

2.3 Methods of Multi Criteria Decision Support (MCDS)

The methods of Multi Criteria Decision Support aim to evaluate a set of mutual exclusive decision alternatives of which at least one should be chosen. As the naming suggests these methods consider a variety of criteria with different influences regarding the overall objective. Especially the comparison of criteria with diverse characteristics, e.g. quantitative and qualitative criteria, is one of the main challenges for MCDS methods.

Utility Value Analysis (UVA)

The UVA is a well-known decision support method that is especially popular among decision makers in the industrial practice due to its quick and simple applicability. The UVA requires the decision maker to define a set of decision criteria and manually assign each criterion a weight with regard to its performance for the overall objective. The sum of all weights must therefore be exactly 100%. Afterwards every solution alternative is evaluated for each criterion according to a previously defined scale, e.g. from 1 to 10. Summing up all weighted ratings yields a utility value for each alternative[12].

The advantage of the method lies in its user friendliness, since the process can be easily explained and communicated. Furthermore the analysis does not necessarily require software support but can also be done with pen and paper. However the weighting is often obtained by rough estimation and the process is rather error-prone, so the method is only recommended for basic decision situations.

Analytic Hierarchy Process (AHP)

The AHP is a matrix-based decision support method that is mathematically more extensive than the UVA. However its principle of pairwise comparison of each alternative with each other for every criterion does not only empirically deliver better decision results but also does not require the definition of a common evaluation scale, thus reducing the methodological effort[13]. Calculating the eigenvector of each comparison matrix delivers a precise ranking of all alternatives for every criterion. The weighting of the criteria is also performed by pairwise comparison and the final ranking of the alternatives can be obtained after a consecutive series of matrix operations. Additionally the inconsistency of the comparison matrix can be mathematically calculated, therefore verifying the logical correctness of the process.

Although the AHP shows better empirical results for many decision situations compared to basic methods as the UVA, the higher complexity of the process requires more personal efforts as well as the use of dedicated business software, e.g. spreadsheet processing tools[14].

Analytic Network Process (ANP)

The ANP is a generalized approach of the AHP where instead of the strict top-down criteria hierarchy an omnidirectional network of criteria and alternatives is allowed[15]. The main advantage for an evaluation is the possibility to not only compare all alternatives for each criterion but also compare all criteria with respect to each available alternative. That means the weighting of the criteria is not constant for the whole decision process but is individually distinctive for every alternative. This unique feature of the ANP enables a problem-specific adaption of the weights which takes the characteristics of the alternatives into account. One example is a criterion that is generally of high importance for the decision, e.g. safety. However if all alternatives fulfill that criterion to a very high extent, the ANP would allow a reduction of the relative weight of this criterion since the other criteria gain in importance. Just like the AHP, the ANP is mathematically rather extensive and requires certain software tools and computing power. However the outcome quality suggests using the ANP as method for complex decision problems.

Since all of the mentioned MCDS methods have different strength and weaknesses the choice of method must be carefully conducted with respect to the specific task at hand. With regard to the assessment of different alternatives within the integrative production system development an evaluation must be easy to execute or even automatized but also appropriate to the rising complexity of the system during development. For this purpose an approach for the assessment of production system alternatives during early development phase will be proposed in the next section.

3. Assessment of Production System Alternatives

As described in the previous section the selection of production system alternatives is a highly extensive decision process with a variety of different criteria characteristics. Methods of Multi Criteria Decision Support enable the evaluation of alternative production systems by comparing diverse criteria and ranking the alternative with regard to the decision maker's preferences. A corresponding approach for the assessment of production system alternatives will be proposed in this section.

3.1 Clustering of Decision Criteria

The review of MCDS methods in the previous section illustrated the importance of the criteria selection for an efficient decision process. Based on the four basic views of SysML as well as the four partial models of CONSENS a clustering of criteria is proposed in Figure 4, together with example criteria for each cluster. While the clusters for the evaluation of processes, resources, behavior and shape comprise specific criteria, the requirements cluster describes the degree of fulfillment of the requirements. Since the requirements diagram contains compulsory as well as optional requirements, all production system alternatives satisfy the requirements to a certain degree. Therefore the requirements cluster represents a central part of the production system assessment.

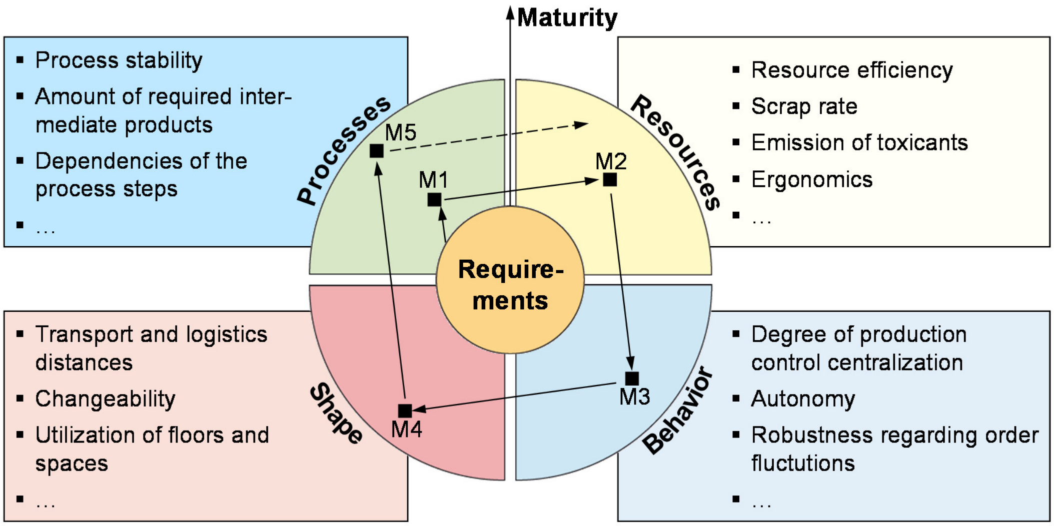

Fig. 3. Criteria clusters and according examples for the assessment of production system alternatives with increasing maturity of Milestones M1 to M5 (polar maturity axis).

Clustering the criteria according to the principal development sequence is the core of a development-parallel assessment in the early design phase. Instead of comparing a fixed set of criteria that is only available for fully specified production systems, each cluster can be independently evaluated from one another. As long as only information for the first clusters are available, e.g. processes and resources, only these clusters will be considered for the selection of alternatives. With increasing maturity of the alternatives (Milestones 1 to 5 in Fig. 4) more facts are known about the different production system specifications and can hence be integrated into the decision process.

3.2 Criteria Weighting and Evaluation of Alternatives

As described in section 2.3 there are numerous approaches for the assessment of a mutual exclusive set of decision alternatives with regard to a defined set of criteria. However the described approaches vary in their degree of formality as well as in the precision of the results. It is therefore advisable to proceed in a three stage process along the maturity of the production system specification as it is displayed in Figure 5.

In the beginning of the development process only fuzzy and incomplete information are known about the available production system alternatives, therefore an advanced evaluation process is not efficient. The UVA is a proven tool to obtain a first ranking and gain an overview of potential favorites (Stage 1). With proceeding development progress more and more solutions are eliminated and the information density for every alternative is growing. The AHP formalizes the rating and evaluation process, thus increasing the decision quality (Stage 2). With only a few favorite solutions left and an almost complete system specification the ANP allows the alternative-specific evaluation of criteria which furthermore improves the precision of the decision process (Stage 3).

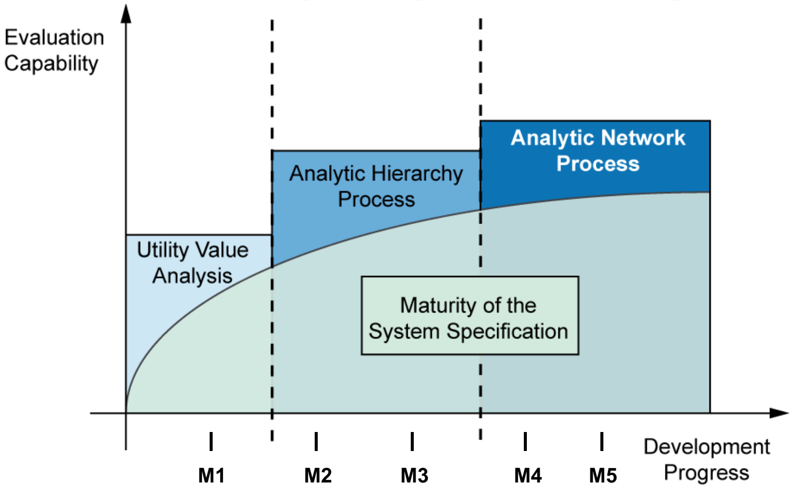

Fig. 4. Choice of MCDS method along the production system development process with increasing maturity of Milestones M1 to M5.

To enable a seamless evaluation process with increasing maturity from Milestone M1 to M5 it is mandatory to provide a common database so that subsequent evaluation methods can directly access the data that have already been provided. From M1 to M2 there is a shift from a single direct evaluation according to a common scale to an evaluation by pairwise comparison. For those criteria that have already been evaluated at M1 the relative criteria evaluation at M2 can be transferred to the evaluation matrix as default proposal. Likewise all decision information that have been obtained at M3 can be transferred to M4 accordingly. This procedure saves unnecessary input of redundant information that have already been provided and focusses on those criteria or information respectively that have not been evaluated before. However it is nevertheless necessary to re-evaluate previous criteria if system aspects have been updated during the course of development and a new outcome of the evaluation is expected.

3.3 Application example

To demonstrate the previously described approach the production of a pedal-electric bicycle, a so called pedelec, is assumed. A pedelec is a mechatronic product that integrates the classic mechanical components of a common bicycle with an electric motor and a control unit that regulates the degree of electric support for the driver. After a first principle solution for the pedelec itself has been proposed, the integrative development of the production system is initiated. The overall objective is the identification of the most cost-effective production system.

1. The requirements list of the pedelec is extended with aspects that are of particular importance for the manufacturing and assembly of the product. The information are derived from the business model of the product, which states that the pedelec shall be a technology leader in its class and display a long-lasting durability. The implementation of the business model into the requirements results for example in a minimum production rate of 2000 p.a. and that as few sole-purpose-tools as necessary are to be used for the production. The more optional requirements are fulfilled by a production system alternative the better is the rating for this particular cluster.

2. Based on the principal structure as well as a first shape model of the pedelec, the process sequence is derived. Alone for the production of the pedelec's frame the development team identifies five principle process chains that are capable of producing the frame according to the requirements. The process chains differ in the forming and joining technologies, e.g. welding, casting or forging as well as the sequence and sourcing of process steps, e.g. internal preheating or external post-treatment. As demonstrated in Table 1, with a first UVA every specified process chains is rated from 1 to 10 for each of the weighted criteria. The development team decides to eliminate the lowest-rated alternative "Forging External" since this alternative also shows the lowest degree of requirements fulfillment. For the remaining four process chains a resource model is then to be elaborated.

Table 1. Exemplary UVA of Production System Process Criteria.

	Process Reliability		**Process Complexity**		**Material Density**		**Weighted**
	Weight	Rating	Weight	Rating	Weight	Rating	**Sum**
Casting Internal		8		7		6	**7.1**
Casting External		6		4		7	**5.9**
Welding Internal	40%	9	25%	8	35%	8	**8.4**
Welding External		7		5		9	**7.2**
Forging External		6		5		6	**5.8**

3. Specified resource models for each of the four remaining process chains constitute a more precise decision basis with more complex criteria. The development team switches to the AHP method with the previous evaluation results being adopted as initial ranking. However the remaining alternative solutions are now compared pairwise for all criteria according to a linguistic scale, where 1 means equality and 9 means total dominance. By this pairwise comparison among the criteria and between the alternatives for each criterion a consistent weighting as well as the evaluation of the alternatives is obtained. An example for the evaluation of the criterion "Resource Efficiency" is given in Table 2. Corresponding tables then have to be derived for all other criteria to obtain the weighted result. The ranking identifies three favorite solutions and the lowest-rated alternative is disregarded.

Table 2. Exemplary pairwise comparison and obtained ranking for criterion "Resource Efficiency".

Resource Efficiency	Casting Internal	Casting External	Welding Internal	Forging External	**Normalized Eigenvector**
Casting Internal	1	5	3	6	**55.4%**
Casting External	1/5	1	1/2	5	**15.1%**
Welding Internal	1/3	2	1	6	**24.4%**
Forging External	1/6	1/5	1/6	1	**5.1%**

4. For each of the three selected alternatives a behavior model is developed. The behavior model includes information about the production control strategy as well as possible responses in case of machine failure or order modifications. Those criteria evaluations that have already been conducted with regard to the three remaining solutions are imported from the database. The comparison of alternatives then only has to be executed for new criteria. The weighting of the criteria must be repeated for the full set of criteria at that point of time. The team decides to stay with the AHP method and eliminates the new lowest ranking alternative "Casting External".

5. With only two remaining solutions a shape model is developed for each alternative. Shape models consider possible layout configurations for the previously defined specifications and requirements. Due to the different focus of the alternatives and since both alternatives have equally good process ratings, the ANP is used to determine a solution-specific criteria weighting. While casting is especially strong regarding its resource efficiency when the frame is directly produced according to the product specification, welding exhibits a more flexible behavior since the resources can also be used for other purposes. Evaluating the criteria correspondingly returns the final ranking of the two remaining alternatives and the favorite solution "Welding Internal":

1. Welding Internal – 57.8% **2. Casting Internal – 42.2%**

The obtained favorite solution can now be refined and elaborated in more details, for example by iteratively running through the partial models again and aligning it more precise with the product model and its requirements. It is of course also possible to reduce the relevant solutions not only down to one favorite, but proceed with two or more solutions to the second iteration loop.

4. Conclusion and Outlook

The proposed approach for the assessment of production systems focuses on the integrative development of product and according production system during the early design phase. A specific challenge of the early phase is a high amount of incomplete and vague information, thus spanning a big solution space. The described process of sequentially adding criteria during development considers the fact that solutions already need to be compared and evaluated even when they are not fully specified yet to reduce the solution space as early as possible. As has been described the integrative development of product and production system is an extensive task and the complexity rises with ongoing development and maturity of the system. To account for the resulting shift in evaluation requirements a three-stage evaluation procedure has been proposed that focusses on quick and basic measures during the beginning of the development to an advanced methodology for further developed system specifications.

The evaluation is not executed with single domain-specific tools and measure but rather comprises the full specification with all information that are available at the point of evaluation. The proposed methods of MCDS avoid an isolated optimization of parts or sub-modules during development that might negatively affect the overall performance of the system. The evaluation and analysis of the system specification in parallel to the actual system development is therefore conducted in accordance with MBSE principles. However especially the more advanced methods of AHP and ANP require a significant amount of information to effectively assess the alternatives. The methods themselves do not replace a thorough and comprehensive data acquisition of the whole decision situation but can only support the developer in structuring and analyzing the available information.

In the future it is planned to elaborate a suitable data structure that can fulfill the demand of one common database for the input and output of all consecutive evaluation methods. This database is the key to achieve acceptance among potential users and system developers since it avoids gathering the same information twice. It must also include interfaces to the enterprise resource planning systems to automatically obtain data that can be used for evaluation purposes. The overall objective for the described approach remains a maximum degree of automation for the evaluation process to allow the developer focusing on the creative part of the task instead of formal measures.

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