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An uncertainty-based evaluation approach for human-robot-cooperation within production systems

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Abstract

The rising global trend towards mass customization embodies a major challenge for future production systems in terms of reconciling productivity with flexibility. Moreover, external factors such as varying lifecycles and shifting boundary conditions due to the demographic change intensify the severity on determining a suitable level of automation and changeability. Within this context, human-robot-cooperation offers a promising solution in order to cope with future demands towards flexible production systems. While most assembly design methods focus on interrelations between functionality and performance, the dependency of a varying economical feasibility due to an increased changeability potential within human-robot-cooperation is not considered so far and furthermore cannot be represented using conventional methodologies. Hence, the consistent comparability between system alternatives with variable degrees of automation is aggravated, representing the primary problem. This work presents a methodology for an uncertainty-based economical evaluation of flexible human-robot-cooperation workplaces in assembly systems that catches the intricate nature and interrelations of internal and external factors and hence, comprising varying flexibility demands. The comprehensive cost model design takes into account uncertainties and thus, incorporating a more robust monetary evaluation within the scope of turbulent environment. Consistent reference scenarios are generated using a scenario-driven approach for quantitative uncertainties comprising both descriptive as well as prescriptive methods within the definition stage of prospective influencing parameters. Based on simulations a comprehensive analysis and interpretation of inherent risks and chances can be derived and consolidated enabling the overall quantitative assessment of system alternatives. The application of the uncertainty-based evaluation model is exemplarily shown using an automotive case study. The potential for the methodology supporting the planning and design phase is demonstrated via the assessment of the internal flexibility provided by alternative systems and matched with probability-based scenario attributes in order to obtain an optimized operation point.

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Keywords: Assembly; Flexible manufacturing system; Cost

1. Introduction

Industrial companies are facing numerous challenges, namely dynamic markets, volatile consumer behavior [1] and the demographic change [2] altogether leading towards turbulent environments [3]. The increased complexity originates from both internal factors (technologies and products) as well as external factors (customers and political framework) [3].

In this context, the trend from mass production to mass customization embodies a major source for the rising complexity [4,5] that needs to be mastered by future production systems. This circumstance forces enterprises to shift their focus to flexibility initiatives under the premise of meeting economic productivity objectives in globalized markets. As a matter of fact, flexibility and changeability have been major issues in research for a couple of years focusing on overall evaluation and implementation strategies [6,7], but leaving out the significant decision process [8]. The evaluation and decision process is rather experience-driven and provides limited applicability for industrial practice [9].

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The assembly, as a final phase of the industrial value chain, represents the key process for product realization and individualization. Hence, it entails a major share in overall manufacturing costs [10] comprehending a significant demand in terms of flexibility and changeability. While hybrid assembly systems based on human-robot-cooperation represent a promising approach coping with the aforementioned challenges by an adequate synthesis of individual strengths [11,12], systematic methodologies for their assessment are either missing or solely focus the initial operation stage [13]. Nowadays, the assembly planning process is dominated by economical operating figures generally highlighting productivity and line capacity. The performance of sensitivity analyses with varying data are often not considered [14], though comprehending an uncertain framework with tremendous possible impact on costs along the expected product life cycle [15]. In general, existing approaches using tree-based discrete system states support stochastic decision problems, but the fast complexity gain limits the applicability [16].

The decreasing predictability of future costs, risk factors and flexibility demand as a result of increased dynamic and complexity impedes the planning phase. As a consequence, conventional evaluation approaches by calculating one deterministic Net Present Value (NPV) are not sufficient in order to compare flexible assembly solutions based on human-robot-cooperation with state-of-the-art solutions.

2. Objective and Paper Structure

The objective of this research is to provide a modeling approach enabling the uncertainty-based evaluation of human-robot-cooperation in the field of assembly system design and planning. First, an evaluation framework based on the receptor-model is introduced [9]. The identification and quantitative modeling of relevant input factors represent the subsequent step. One major advantage is the consideration of dynamic interdependencies between the input factors at operational level. As a final step, an automotive final assembly line is chosen as an exemplary case study in order to apply and evaluate the proposed methodology. The paper concludes with a discussion of advantages, limitations and potential applications, and furthermore, outlines opportunities for further research activities.

3. Evaluation Model

3.1. Model Structure and Methodology

The evaluation framework as depicted in Fig. 1 comprises of two interacting models: the uncertainty model and the cost model. The general purpose of the evaluation model is a feasible application. In order to achieve this, a comparable uniform target value (TV) has to be selected. This objective can be realized by solely considering crucial cost elements. To exemplify the methodology, the observation focus shall be directed to flow line assembly systems, such as to be found within the final production step in the automotive industry. Here, two major assumptions shall be valid:

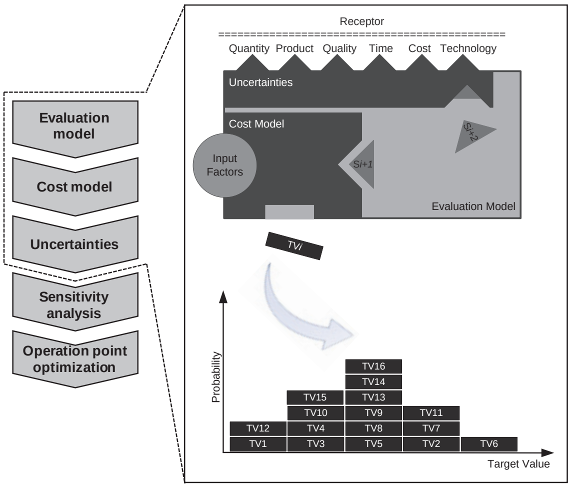


Fig. 1. Methodology overview.

- The cycle time of the line is pre-determined with respect to the aimed capacity of the system or plant.
- The methodology focuses on workspace level and not on system level with complex coherence between up- and downward assembly stations.

The selection of a concept alternative within the assembly system design and planning stage always leads to a competitive evaluation, followed by the realization as well as implementation of the favored alternative. The utilization of a comparative cost approach simplifies the formal solution since individual benefits can be neglected.

The uncertainty model incorporates internal as well as external influences on the final assembly line. Using the scenario analysis, arbitrary combinations and permutations of facts and changes result in scenarios representing possible plausible and predictable future characteristics. As a subsequent step, these uncertainties are formally modeled via stochastic distributions representing the input domain for the following risk analysis using the Monte Carlo Method (MCM). Based on the formal validity of the stochastic distributions representing the quantitative uncertainty the input factors can be derived by drawing. An aggregated set of random drawings represents a scenario or a state (S) that needs to be integrated into the cost model in order to determine the corresponding TV.

3.2. Life Cycle Perspective

Assessing manufacturing systems requires a product-centered perspective corresponding to the life cycle cost (LCC) approach as a key economic evaluation of system alternatives. It takes into account cost shares that incur before, during and after production [17].

Changes in terms of product or process require distinct modifications on system and workspace level. The system flexibility refers to a pre-defined corridor where a system can react to these changed requirements with minimum additional costs involved [18]. Moreover, the term changeability represents the major characteristic in reacting to unforeseen changes in a fast as well as cost-efficient way [9]. The induced costs are labeled as changeability costs [18,19] and enable the overall quantitative comparability of system alternatives within the evaluation model.

4. Identification and Modeling of Input Factors

4.1. Input Factors

The contemplation of input factors as receptors and their individual prioritization addresses two main contributions. Primarily, by focusing on weighted key receptors the selection of a distinct solution among feasible alternatives is facilitated. Therefore, it is possible on a more detailed level of resolution to focus on relevant evaluation criteria according to the individual market-driven enterprise strategies. Secondly, a key advantage is represented by the modularity of the receptors that can be individually extended enabling a highly dynamic customization to project-specific economical requirements and objectives.

In order to simplify the modeling effort, it is reasonable to deliberately neglect factors that can either be regarded along the product life cycle as indifferent or that underlie common leveraging effects along all concept alternatives.

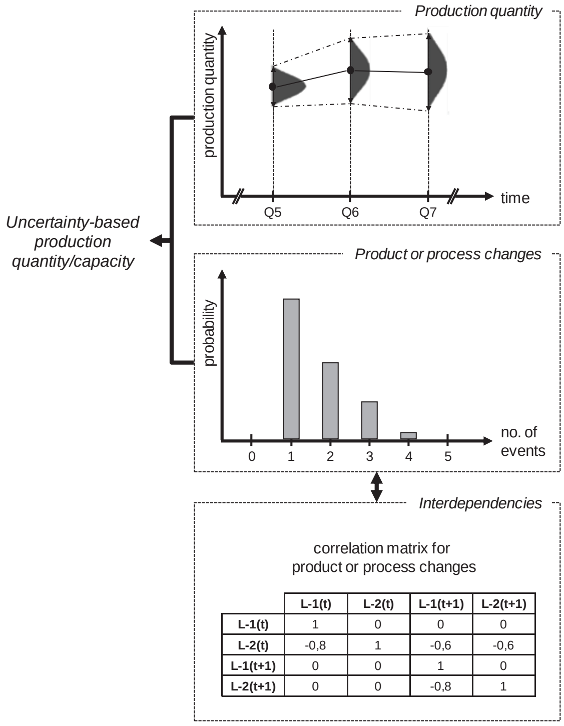
Here, it is important to formally distinguish two classes of uncertainties with respect to their occurrences [19]:

- *Continuous uncertainties* – this class refers to input factors that have a continuous and inevitable influence along the designated product life cycle on the system alternative, e.g. wage level.
- *Discrete uncertainties* – events along the product life cycle that directly trigger and affect the inherited flexibility potential of the assembly system. These events are based on significant changes in terms of product, process, standardizations or political framework. Regardless of the main cause, these events will result in changes within the assembly process or the structure.

4.2. Production Quantity

The production quantity or production output represents a significant input factor. Nevertheless, it is important to realize that the ideal development of values representing balanced capacity utilization within a production network is rarely to encounter in reality. The actual course resembles the classic life cycle course with phases ramp-up, saturation and end-of-life [11]. However, due to capacity balancing it is hardly possible to derive actual production numbers from documented sales quantity. These discrepancies may have different causes. Primarily, these are the varying degrees of in-plant production components and local make-or-buy strategies together with shifted customer or production orders.

Within the scenario analysis, the variation of production quantities is associated with a high chance. In order to catch the intricate nature and process the probabilistic behavior it is reasonable to segment the product life cycle into repeatable time periods.



correlation matrix for product or process changes

	L-1(t)	L-2(t)	L-1(t+1)	L-2(t+1)
L-1(t)	1	0	0	0
L-2(t)	-0,8	1	-0,6	-0,6
L-1(t+1)	0	0	1	0
L-2(t+1)	0	0	-0,8	1

Fig. 2. Production quantity and capacity modeling.

Here, it is important to mention the level of resolution. The shorter the time periods are, the higher is the computing complexity in aggregating the cumulated risk within the chosen solution space. A fair and reasonable balance between modeling complexity and required level of detail has been proven by applying time periods on quarterly basis as illustrated in Fig 2. Within this time frame it is advantageous to further distinguish on weekly basis in order to simulate minor deviations due to vacation periods or foreign exchange impacts and consolidate them via interpolation.

However, the production quantity, as an equivalent to the demanded capacity, can be formally described as a time-dependent, predecessor-independent and continuous random variable, and thus can be modeled using the beta distribution for each distinct time period. Here, the predicted trend is regarded as the global peak and the minimum and maximum boundaries are derived from the scenario analysis along the chosen life cycle.

4.3. Direct Production Costs

Forecasts or data base analysis enable the course prediction of labor costs representing the major share within the group of direct production costs. The combination of both descriptive with prescriptive approaches enables setting the required data base for the following scenario analysis. Under consideration of a nominal labor cost index it is reasonable to deduct a retrospective course. Moreover, by using scientific quantitative forecasts it is possible to predict mid-term developments. Here, the labor costs are regarded as a time-dependent but predecessor-independent continuous random variable, and thus enabling the application of a beta distribution function to formally specify this uncertainty. In order to simplify the mathematical modeling, a time-discrete approach on annual basis shall be applied. Instead of absolute values, it is more consistent to work with relative cost developments. This approach covers interrelated change sequences due to overall social-economical developments, such as order situations and demographic change leading to skills shortage.

4.4. Product or Process Changes

Events along the product life cycle, such as product modifications have a varying impact on the assembly system. As mentioned before, modifications in terms of product, revised standards or the introduction of novel production technologies lead to assembly process changes and assembly system structure changes. Hence, this results in alternating cost for the desired degree of changeability. However, it is essential to distinguish between the possible changes and to introduce classes in order to categorize and handle the level of complexity.

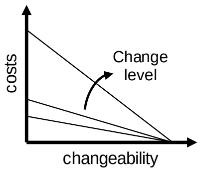
Level-1 (L-1) changes refer to minor alterations and modifications that can be conducted during intervening periods between production shifts or even during downtime. In contrast, level-2 (L-2) or level-3 (L-3) changes require several days up to few weeks where the production line needs to be paused (see. Table 1). Besides planned and determined events, such as the introduction of new model variants or product updates, there exists a wide range of random and unpredictable events. In general, companies tend to bundle and focus these changes in order to minimize disturbances on normal production operation. Manufacturing changes with high priorities, such as recalls that are unlikely to be properly scheduled need to be integrated into daily operation. In this context, exemplary causes for events are:

- Design updates,
- cost-reduction,
- quality improvement and
- changes due to legal terms, specifications or regulations.

The fact that the duration of the events is insignificant compared to the complete product life cycle, it is feasible to assume that no event will occur during the major time period. Hence, this authorizes the utilization of the Poisson distribution in order to characterize discrete events. Since L-3 events correspond to major changes that significantly affect the production operation for few weeks, such as integration of new product models, this change type can be omitted due to the lack of uncertainty. A simplified approach can be conducted by limiting the Poisson distribution as seen in Fig. 2. This is valid since the number of planned changes is unlikely to go below the designated target value, and thus allowing directly using the expectancy value and only applying a single-sided distribution.

Table 1. Exemplarily change cost structure and interdependency between changeability and change level.

Cost group	**L-1**	**L-2**	**L-3**
production resources			x
logistics, supply chain	x	x	x
workspace design			x
installation, alteration	x	x	x
initial operation		x	x
training			x
…			



Changes of internal as well as external input factors might inflict additional costs that need to be integrated into the evaluation model in order to guarantee a comparative analysis of alternatives. Introducing the two dimensions direct cost and non-productive time, it is possible to enable a standardized view for different level of changes along the product life cycle. As stated in [22], a high automation level impedes the overall changeability while other aspects, such as mobility, modularity or standardization enhance it.

4.5. Interdependency among Uncertainties

Correlation coefficients as depicted in Fig. 2 enable the modeling of system interdependencies among the assumed uncertainties [23]. It is reasonable that L-1 events do not have an influence on other events, since their implementation is preferably done without interference with normal production operation. L-2 events on the other hand need to pause production for several days. This results in a probable accumulation of L-1 changes and a desired combination with L-2 changes in order to reduce the induced downtime. On a similar base, it can be reasoned that L-2 events reduce the willingness and therefore the probability to carry out an additional major structural modification in the subsequent year. On the other hand, the probabilities of combining both measures or shifting one measure are much lower, and thus leading to a decrease of the correlation coefficient.

5. Case Study

5.1. Requirements Analysis and Modeling Phase

The methodology is exemplarily illustrated using an automotive case study focusing the selection of a final assembly station among feasible system alternatives. As aforementioned, the two key objectives are economical efficiency and robustness of the decision.

Within this case three alternatives are contemplated. Besides a manual assembly, two assembly concepts comprising human-robot-cooperation are considered. Based on the introduced taxonomy in Fig. 3 the characteristics can be formally specified and distinguished:

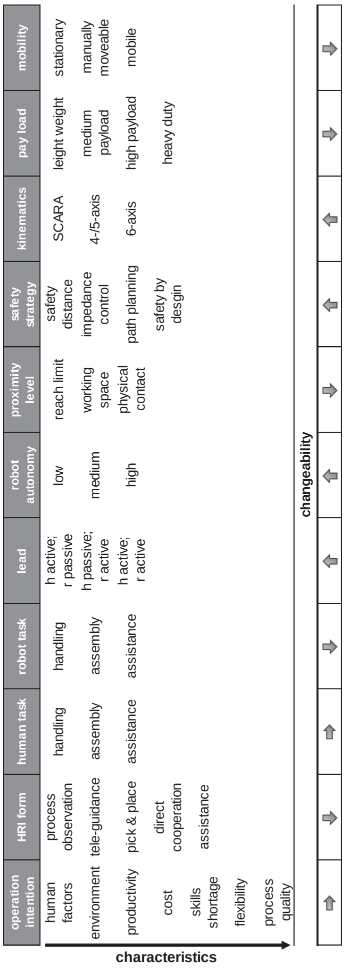


Fig. 3. Taxonomy for human-robot-cooperation with respect to changeability (based on [23])

- *Concept 1: manual assembly* – the human worker is responsible for handling as well as the subsequent assembly.
- *Concept 2: human-robot-cooperation* – a robot undertakes a subtask of the assembly process while the human worker takes over and executes handling and the final assembly step
- *Concept 3: human-robot-coexistence* – a robot undertakes the handling and assembly process while the human worker carries out additional tasks individually.

The environment accommodates uncertainties that cannot be explicitly handled using one-dimensional assessments. A comparative analysis of the taxonomy characteristic results in distinct changeability degrees representing the key indicator to cope with product or process changes, and thus indicating varying changeability costs.

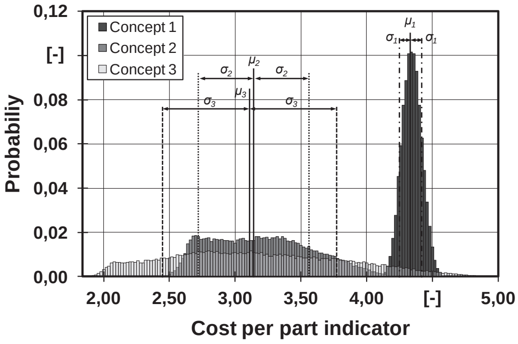


Fig. 4. Cost distribution from MCM (n = 60.000).

Contemplating and ranking all input factors, the major influences can be deducted and systematically investigated using the scenario analysis deriving the individual significant corridors. As a result, the probabilistic modeling of the uncertainties can be conducted and these data can be further forwarded towards the subsequent risk analysis. Summarizing the characteristic of this case, the following input factors were identified and modeled:

- production quantities,
- manufacturing costs,
- resource costs (e.g. energy),
- number of changes or incidents due to product or process modifications and
- concept-specific technical availability.

5.2. Concept Selection

The MCM computes probabilistic TVs for the system alternatives incorporating the quantitative uncertainties as depicted in Fig. 3. Applying a eight-step-approach evaluation process based on probabilistic characteristics [24-26], a robust decision can be derived. These hierarchic steps are as follows:

1. μ-criteria,
2. μ-σ-criteria,
3. stochastic dominance,
4. statewise dominance,
5. first-order stochastic dominance,
6. second-order stochastic dominance,
7. risk ratio and
8. sensitivity analysis

It can be deducted that there is a statewise dominance of concept 2 over concept 1. Furthermore, considering the risk ratio, concept 2 has an advantage over concept 3, and thus represents a promising solution.

5.3. Operation point optimization

Applying a sensitivity analysis yields systematic identification of main contributors leveraging the designated TV in terms of expected value and standard deviation. Factors with high impact are:

- personnel demand,
- development of labor costs,
- development of production quantity,
- buffer size and
- no. of assembly stations between buffers.

On a more detailed level, it is reasonable to clarify and determine the cost effectiveness of the individual input factors to leverage more purposive design changes during the concept phase. Initially, the influence range can be compared in pairs and concept selection or changes can be supported by trade-offs considering the decision process of the designated TV. A more comprehensive systematic approach comprising multiple input variables can be conducted by applying an Analytic Hierarchy Process (AHP), such as in [17].

6. Summary

Facing dynamic and steadily uncertain markets, this paper introduces an approach to enhance conventional economic evaluation with uncertainties in order to derive a probabilistic evaluation methodology. It is designed for comparing assembly systems with varying flexibility and changeability potential in order to meet turbulent and unknown internal and external input factors that might significantly influence the economical efficiency. The presented cost model considers different aspects in terms of changeability, maps the relevant changeability costs with distinct uncertainties and integrates them in the evaluation framework. In order to enhance the plausibility of the results, a combination of scenario analysis and risk analysis is proposed, since a methodology solely focusing on scenario analysis cannot provide the desired robustness. The intermediate results are then firstly, processed for the formal quantitative description of the uncertainties and secondly, used during the subsequent computational MCM. This allows a combination of both documented retrospective developments together with distinct quantitative studies in order to establish an integrative descriptive-prescriptive approach. As a result, the synthesis of both methodologies allows a step-by-step evaluation methodology enabling a more robust decision foundation for assembly system design and planning projects incorporating human-robot-cooperation.

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