Development of a Rating System by means of Extended Economic Appraisal using the Digital Twin for the Design of Cyber-Physical Production Systems

by

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Declaration

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Abstract

This study seeks to develop a rating system for the comparison of alternative production configurations, which incorporates criteria that are difficult to quantify. The increasing demand for individualization down to batch size 1, coupled with rising price pressure, ambitions to ensure good working conditions, and desire to meet sustainability goals, is forcing manufacturers to optimize their production systems comprehensively. Decisions on production order planning are currently based predominantly on quantifiable aspects, such as available resources and the corresponding financial means, while criteria that are difficult to quantify, such as the adaptability of the production system and the well-being of the employees, are regularly disregarded. This research thesis presents a comprehensive approach of a holistic rating system for the design of cyber-physical production systems (CPPS). The rating system combines a production scenario configurator with a simulation of occupation planning and an economic appraisal extended by the work system value. The aim of the research is to provide a procedure for the short-cycle determination of the most suitable smart production system for small batches, considering assessment dimensions that are expected to have long-term economic, ecological, and social value, and relevance. To achieve this, the simulation is expanded and rating formulas are applied that concentrate the information content while facilitating decision-making. Following the design science research methodology, this study covers both a quantitative and qualitative literature analysis of selected publications to derive a set of work system value criteria relevant to CPPS, and identifies indicators to operationalise them. This is followed by the abductive design of a digital twin-based configuration and rating tool, which is deductively validated with collected data from Werk150, the learning factory of the ESB Business School on the campus of Reutlingen University.

The configuration element of the system suggests different possible production scenarios. These result from a variation in the form of production organisation, which entails a change in the division of labour and activity sequencing, as well as the allocation of available devices and agents. In order to make a comparison between the configured scenarios, an extended economic appraisal (EEA) is applied to each; it fuses a partial cost calculation to a work system value. The partial cost calculation is tailored to the aspects that differ between the production variants, material costs, and employee costs. The work system value, which extends the economic appraisal consists of weighted criteria: physical and mental stress; ecology; competence fit; delivery reliability; capacity utilisation; error potential; various flexibility corridors; all of which enable the utility comparison of alternative production scenarios. Information needed to anticipate the partial costs of production scenarios is provided by a time discrete simulation, which considers the properties of the different scenarios. The work system value also takes information from the simulation, but adds to it data collected from experiments.

Opsomming

Hierdie studie poog om 'n graderingstelsel te ontwikkel vir die vergelyking van alternatiewe produksiekonfigurasies wat kriteria insluit wat moeilik is om te kwantifiseer. Die toenemende vraag na individualisering tot by groepgrootte 1, tesame met stygende prysdruk, ambisies om goeie werksomstandighede te verseker en die begeerte om volhoubaarheidsdoelwitte te bereik, dwing vervaardigers om hul produksiestelsels omvattend te optimaliseer. Besluite oor produksiebestellingbeplanning is tans hoofsaaklik gebaseer op kwantifiseerbare aspekte soos beskikbare hulpbronne en die ooreenstemmende finansiële middele, terwyl kriteria wat moeilik is om te kwantifiseer, soos die aanpasbaarheid van die produksiestelsel en die welstand van die werknemers, gereeld verontagsaam word. Hierdie navorsingstesis bied 'n omvattende benadering van 'n holistiese graderingstelsel vir die ontwerp van kuber-fisiese produksiestelsels (KFP) voor. Die graderingstelsel kombineer 'n produksiescenario-konfigureerder met 'n simulasie van beroepsbeplanning en 'n ekonomiese aanslag wat met die werkstelselwaarde uitgebrei word. Die doel van die navorsing is om 'n prosedure te verskaf vir die kortsiklusbepaling van die mees geskikte slim produksiestelsel vir klein groepies, met inagneming van assesseringsdimensies wat na verwagting langtermyn ekonomiese, ekologiese en sosiale waarde en relevansie sal hê. Om dit te bereik word die simulasie uitgebrei en graderingsformules word toegepas wat die inligtingsinhoud konsentreer terwyl besluitneming vergemaklik word. Na aanleiding van die ontwerpwetenskapnavorsingsmetodologie dek hierdie studie beide 'n kwantitatiewe en kwalitatiewe literatuurontleding van geselekteerde publikasies om 'n stel werkstelselwaardekriteria af te lei wat relevant is vir KFP en identifiseer aanwysers om dit te operasionaliseer. Dit word gevolg deur die ontvoerende ontwerp van 'n digitale tweeling-gebaseerde konfigurasie- en graderingsinstrument wat deduktief bekragtig word met versamelde data van Werk150, die leerfabriek van die ESB Business School op die kampus van Reutlingen Universiteit.

Die konfigurasie-element van die stelsel stel verskillende moontlike produksiescenario's voor. Dit spruit uit 'n variasie in die vorm van produksie-organisasie, wat 'n verandering in die verdeling van arbeid en aktiwiteitsvolgorde behels, sowel as die toekenning van beskikbare toestelle en agente. Ten einde 'n vergelyking tussen die gekonfigureerde scenario's te maak, word 'n uitgebreide ekonomiese beoordeling op elkeen toegepas; dit smelt 'n gedeeltelike kosteberekening saam met 'n werkstelselwaarde. Die gedeeltelike kosteberekening is aangepas vir die aspekte wat verskil tussen die produksievariante, materiaalkoste en werknemerkoste. Die werkstelselwaarde, wat die ekonomiese beoordeling uitbrei bestaan uit geweegde kriteria: fisiese en geestelike spanning; ekologie; bevoegdheids pas; afleweringsbetroubaarheid; kapasiteitsbenutting; fout potensiaal; verskeie buigsaamheidskorridors; wat almal die nutsvergelyking van alternatiewe produksiescenario's moontlik maak. Inligting wat nodig is om die gedeeltelike koste van produksiescenario's te voorsien word verskaf deur 'n tyddiskrete simulasie wat die eienskappe van die verskillende scenario's in ag neem. Die werkstelselwaarde neem ook inligting uit die simulasie, maar voeg daarby data wat uit eksperimente versamel is.

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List of Acronyms

API	Application programming interface
GNB	Gaussian naive Bayes
CPPS	Cyber-physical production system
CPS	Cyber-physical system
CSR	Corporate social responsibility
CSV	Comma separated values (file format)
DIN	Deutsches Institut für Normung (German Institute for Standardization)
EEA	Extended economic appraisal
FLS / MES	Manufacturing Execution System (Fertigungsleitsystem)
HRC	Human robot collaboration
I4.0	Industry 4.0 (Fourth Industrial Revolution)
KFP	Kuber-fisiese produksiestelsels
KNN	K nearest neighbour
MLP	Multilayer perceptron
MU	Monetary units
PRI	Production reconfiguration index
PCI	Production customisation index
REFA	Association for Work Design, Company Organisation and Corporate Development (Verband für Arbeitsgestaltung, Betriebsorganisation und Unternehmensentwicklung e. V.)
va	Value added
VPN	Virtual private network
Werk150	Factory of the ESB Business School on the campus of Reutlingen University

Chapter 1
Introduction

In this section, the background and objectives of the research work are presented. The chapter contains an analysis of the initial situation and the problem from which the vision and the concrete scope of the work are derived. The following diagram provides a summary overview of the elements that are dealt with in more detail in this chapter and which are the starting point for the framework of this thesis.

Initial Situation	Problem statement	Target setting
Fundamentally, production can be understood as a highly dynamic socio-technical system that can only survive if it can adapt to its environment [Cf. Westkämper et al., 2016, p. 50]	The high degree of complexity and need for integration, which define the current times, require a systematic approach when adapting production structures [Cf. Löffler, 2011, p. 4] New assessment bases that integrate the flexibility and changeability of the systems must be developed in the future [Cf. Besenfelder et al., 2017 p. 5]	(Semi)autonomous design of an optimal production structure both for monetarily quantifiable aspects and for qualitative non-monetary aspects Quantifiable aspects: technical and financial Qualitative aspects: medium and long-term returns from innovations in technology, work organisation, qualification and health [Cf. Neubauer et al., 2011, pp. 67-68]

Figure 1: Initial situation, problem statement and target setting (Westkämper and Löffler 2016; Löffler 2011; Besenfelder et al. 2017; Neubauer and Wächter 2011)

The addressed research gap and the intended scientific contribution of the research work are described as well. In the research design and research methodology, the organisation of the research and the methodological procedure are explained. In addition, the scientific theoretical background of the research project is highlighted. In the concluding section, the structure of the thesis is presented.

1.1 Initial situation and rationale of the research

In industrial practice, cyber-physical production systems (CPPS) have to meet a wide variety of requirements, not all of which can be fulfilled in the same way. It therefore makes sense to weigh up on a case-by-case basis how the maximum overall benefit of production can be achieved. Currently, decisions related to this are largely based on quantitative aspects, such as finances, which do not reflect the totality of system requirements. Aspects that are more complex to quantify, such as flexibility and employee well-being, are often disregarded. Approaches for an extended economic appraisal (EEA) were already developed by scientists decades ago (Bullinger et al. 1997; Rohmert and Luczak 1975), but could hardly gain acceptance in practice. After the recession of 1974/75, a structural policy was implemented in Germany that prioritised the development of new products, technologies and new markets, while the improvement of living and working conditions was considered to be of secondary importance (Hauff and Scharpf 1975). Similarly, operational investment planners and controllers have been criticising the higher computational effort and complexity, as well as the need for interdisciplinary accompanying research on the EEA procedures (Neubauer and Wächter 2011). Digital twins and applications of artificial intelligence, combined with findings from occupational science, now offer new potential for integrating qualitative criteria into the configuration and assessment process of CPPS in addition to quantitative criteria.

1.2 Research problem statement and questions

Increasing demand for individualisation and decreasing depth of added value, as well as growing dynamism and turbulence are trends that are forcing the manufacturing sector to strategically increase its adaptability in production structures (Löffler 2011). In addition, the increasing number of product variants is also driving industrial producers to slowly replace assembly lines with more flexible modular production systems (Mayer and Endisch 2019 - 2019). "Shorter product life cycles, high labour costs, new products and processes, and social and economic change are forcing all manufacturing companies to make ongoing adjustments and improvements to their overall operations." (Wiendahl and Wiendahl 2020) Ambitions to ensure ethical working conditions and meet sustainability targets, as addressed in corporate social responsibility (CSR) reports, are also pushing the manufactures towards an intelligent overall optimisation of production systems to remain competitive in the long term. In order to meet the demand for comprehensive decision-making in the design of production systems, systematic support for the collection and processing of relevant information is required to broaden the basis for decision-making and to facilitate decisions in consideration of multiple requirements.

The central research questions to be answered in this thesis are derived from the initial situation and problem definition that precede the research project. The first research question is: How can a CPPS be evaluated by means of extended economic appraisal? The question arises from the challenge of identifying the necessary factors for a decision and operationalising them with the help of suitable indicators. This research aims to lay the foundation for an evolutive system that can propose and simulate production scenarios and apply an EEA to it, largely on its own. Continuous data collection from real production creates a digital shadow that depicts relevant indicators, enables a comparison between planned and real production and thus continuously improves the accuracy of the forecast. With the help of the simulation, the information from the digital shadow allows a statement to be made about the most ideal production scenario. As this scenario is then implemented in real production, a feedback loop is created between the digital image and reality. This indicates that the informative assistance system is a digital twin. Since the assessment of possible CPPS variants is accompanied by their configuration, the second research question is: How can a digital twin suggest design variants for the CPPS? The combination of the two questions.

How can a CPPS be evaluated using an extended economic appraisal (EEA)?

What are the aims of production in the Werk150?

How can the work system be meaningfully assessed with a systematic approach? What information base is required for this?

What are the roles of the EEA and the human in the process of decision making for a scenario?

How can a digital twin suggest design variants for the CPPS?

Who are the agents or participants of the Werk150 and what functions do they perform?

What parameters and degrees of freedom are available to adjust the system?

1.3 Target setting and research objectives

The basic idea of this research work is that a digital twin simulates different production scenarios, such as the assembly and manufacturing organisation forms, the interactions of the work system agents and the material flow on the basis of current data on the order situation and resource availability. The digital twin of the real factory is intended to enable an automated and comprehensible decision support system that automatically embodies different production scenarios based on insights from the design and appraisal of CPPS and determines a score for each scenario according to the appraisal parameters, thus supporting the decision maker through a pre-selection. In order to illustrate the vision with specific applications that have already become established in everyday life, it is useful to compare it with a navigation system. The navigation system first searches for possible routes and proposes the optimal route for the driver's situation on the basis of current traffic information and big data, which consists of large and complex data sets. Determining which route is considered optimal is a decision made by the driver, who prioritises for example between the fastest route, shortest route, toll or no toll, etc.

In this work, a system is to be created which, as already described, consists of several elements, for each of which the objectives are now presented. A research objective is to define a set of rating criteria for CPPS, to derive formulas for their calculation and to implement them as a calculation tool. A suitable EEA procedure is to be found and, if necessary, adapted. For the provision of data for the calculation, an approach is to be prepared for the processing of experimental data. Furthermore, the aim is to establish an allocation approach for scenarios. The scenarios will then be simulated and the results incorporated into the calculation. In addition, the aim is to establish an allocation approach for scenarios. For the scenarios, the goal is to enable a simulation, the results of which will also be used in the calculation. In brief, the goal is to conceptualise and implement a design artefact that incorporates the assessment logic and supports decision makers in selecting from configured CPPS scenarios.

1.4 Gap in research and research contribution

In industrial practice, decisions regarding production are usually made based on quantifiable, mostly financial, performance indicators. However, this approach is often incomplete, making interdisciplinary collaboration between scientists and practitioners an essential prerequisite for assessing the economic efficiency of comprehensive innovations (Neubauer and Wächter 2011, p. 69), as they also consider more dimensions that have great relevance for the company's success in the short and long term. Since the beginning of the 1970s, management scientists, labour scientists and social scientists have demanded a stronger orientation towards the role and interests of human labour (Neubauer and Wächter 2011, p. 69) and there have been efforts to objectify decision-making by also including aspects that are difficult to quantify in the system evaluation. Well-known researchers have therefore developed concepts for an economic efficiency calculation extended by the missing criteria, which expand a classical cost calculation by the work system value (Rohmert and Luczak 1975; Bullinger et al. 1997). Probably due to additional assessment effort and lack of industrial interest, these approaches could not establish themselves on a broad scale. Nevertheless, some researchers have taken up the ideas and developed advanced evaluation systems for CPPS. Reviewing the assessment dimensions developed at the time and adapting them to the current state of science is one aspect. Above all, however, there is a broad consensus in occupational science that, in addition to economic efficiency, humanism also plays a central role (Neubauer and Wächter 2011, p. 69). Against the background of developing technologies such as digital twins and artificial intelligence, the efforts of an EEA by means of a work system value seem to be easier and more target-oriented to implement, and the potential of acceptance is improved by limited additional work for controllers. EEA for cyber-physical production systems that are applied to real productions can already be found in the literature. Examples include the works by Wulf and Nyhuis (2008) and Wiendahl and Wiendahl (2020) and the dissertation by Keuntje (2019). Likewise, there are approaches to configuring possible production scenarios (Müller 2016; Herzog et al. 2020 - 2020). A combination of the two elements of a production scenario configuration and assessment, using narrow methods, are also presented, for example, by Mayer and Endisch (2019 - 2019) and Michniewicz (2019).

The gap of this research work relates to the configuration of the assembly organisation form and employee allocation, as well as the advanced simulation of production systems in small batch production where a work system value and thus aspects that are difficult to quantify are considered in the EEA of production scenarios. The result is a design artefact that makes it possible to best meet criteria and related assessment dimensions that are based on current scientific knowledge and industrial and social goals as optimally as possible.

1.5 Preliminary considerations on the philosophy of science

The philosophy of science explores the prerequisites for the formulation of scientific statements and is the foundation for the preliminary considerations in the theory of science that decide on which path and under which basic assumptions the intended, systematic and comprehensible gain in knowledge of the research project should take place. Based on these considerations, the questions and goals of the research are formulated and suitable methods are selected. Just as the concept of truth can vary according to context, goal and perspective, so too does the scientific approach to transforming assumptions into knowledge. This research work is based on individual scientific theoretical assumptions, which should be pointed out at this point. Likewise, the preliminary considerations for the development of the research design are highlighted in order to ensure the comprehensibility of the paradigms and to reflect neutrality in the transfer of knowledge. In scientific work, there are several different epistemological positions such as rationalism, constructivism, empiricism and realism. In rationalism, knowledge is based on understanding and reason and not on sensory perception. In constructivism, truth is a construct of the consciousness which constructs reality and knowledge. Empiricism takes sensory perception as the starting point of knowledge and realism assumes that a reality exists that is independent of perception but completed by thought. The epistemological position to be discussed in the research design basically offers two classical relations of cognition and object, positivism and interpretivism. Positivism assumes the possibility of objective perception and thus correspondence with reality. In interpretivism, on the other hand, perception is subject-bound and oriented towards the consensus theory or coherence theory of truth.

Since parts of the study, such as the stress on employees, but also with regard to the design of the rating systematic and the criteria for the holistic comparison of production scenarios, are very strongly influenced by the human factor and its subjective perceptions, such as individual opinions and ethical ideas, an orientation towards the truth concepts of coherence and consensus is suitable in these areas. Access to consensus knowledge is mainly gained with the help of literary works by renowned scholars and through exchange with the supervising professors. The evaluation of the predictability of the artefact's behaviour, on the other hand, is more strongly oriented towards the correspondence concept of truth. This thesis is oriented towards a concrete research question and success is also measured by the validation result in Werk150, on the campus of Reutlingen University. In addition to the research motive, temporal and formal framework conditions are also included in the design and implementation of the study, which indicates a normative character of the thesis. The research questions aim at gaining knowledge that can be used as an applicable design artefact that supports decision-making. Reconciling scientific impartiality and the need for applicable knowledge is therefore a challenge of this research project.

For these reasons this research project is based on the assumptions of the design science research perspective (Vaishnavi et al. 2019; Alturki et al. 2011), which consists of several paradigms and includes both an abductive and deductive phase. In general, the paradigms and assumptions of design science research are unique and cannot be derived from other perspectives such as interpretivism or positivism. The positivist ontology, in which a single reality is assumed to be knowable and probabilistic, can be seen as opposed to the interpretivist ontology of a multiplicity of realities. "Design science research, by definition, changes the state-of-the-world through the introduction of novel artefacts" (Vaishnavi et al. 2019). This allows for alternative states of reality as in interpretivist research and yet assumes a stable unique physical reality that constrains interpretivist multiple realities.

The epistemological approach in design science research is to gain knowledge by making or creating something. The construction is bound to a context. Meaning is revealed through iterative circumscription and exists in the capabilities or, in other words, is evoked by the capabilities. Design science research can be considered a pragmatic approach. In interpretivism, subjects emerge from the relationship between researcher and participant. Positivist epistemology, on the other hand, is unbiased and observes the world objectively. With its claim to predictability of artefact functionality, design science research is closer to natural science than to a positivist or interpretivist approach. Axiologically, creative influence and improvement are in the foreground and not truth as in positivism or situational understanding as in interpretivism. The basic metaphysical assumptions described result in an abductive methodology that, based on a previously gained understanding of the problem and situation, produces a value-adding artefact that can finally be deductively evaluated and validated. The knowledge gained can thus be processed and scientifically communicated.

In design science research, the perspective changes with the process and phases of the research. First, a new reality is created through artefact development, which is compatible with interpretivist views. Then, however, the artefact is analysed positivistic. It is thus also similar to the action research of the interpretivist approach. According to Vaishnavi this methodology unleashes its greatest potential by combining both pragmatic and critical perspectives (Vaishnavi et al. 2019).

The main component of the present research work is to develop a rating systematic according to current scientific, industrial and societal requirements and to present sample applications using a specific use case. With regard to the underlying assumptions that precede the findings of the research work and the goals of gaining knowledge, it can be said that already existing concepts for the EEA of production scenarios and methods for the design of cyber-physical production systems serve as the starting point of the thesis. In order to question the existing conditions and theories and to adapt them to current requirements, the work system value which is used to compare production alternatives is derived anew by redefining and operationalising criteria according to the requirements. An understanding of the state of the art is achieved with the help of both quantitative and qualitative literature analyses. The aim of the work is to create an artefact in the form of a currently relevant systematic that makes it possible to compare scenarios according to quantifiable but also difficult-to-measure qualitative aspects, both for their simulation before implementation and after real implementation. The aim is to enable the most accurate possible statement about the comprehensive scenario performance in both cases. The validation of the developed solution is to be done with the help of the application of the design artefact to the small batch production line of scooters in the Reutlingen Werk150, using data from experiments.

1.6 Research design

The table below summarises the research design, which includes the questions, objectives and methodology of the research.

Table 1: Research design of thesis

Research question	Research objective	Research methodology
1. How can a CPPS be rated by means of Extended Economic Appraisal?	1.1 Overview and analysis of rating methods	Literature review & analysis
	1.2 Definition of rating criteria and required data from CPPS	Design science research: Part 1
	1.3 Concept of a rating system	
2. How can a digital twin propose design variants for the CPPS?	2.1 Overview and analysis of design methods for CPPS	Literature review & analysis
	2.2 Selection and tailoring of a suitable design method for CPPS	Design science research: Part 2
	2.3 Engineering and implementation of a design artefact at Werk150 (HS RT)	
	2.4 Evaluation of the functionalities and limits of the design artefact at Werk150 (HS RT)	

The framework of the research and the chosen techniques are described below. This research project is oriented towards the two central questions of EEA for CPPS and configuration of production alternatives. For the first research question, an analysis of the state of the art will first be conducted to identify existing assessment methods and their characteristics. For this purpose, both a quantitative literature analysis and a qualitative semi-structured literature analysis, which is explained in table 2, are conducted. As shown in the next section, the first part of the Design Science Research Process Model, which is presented in figure 2, is used based on the findings from the literature. On the one hand, the required data of the different CPPS alternatives are defined, which can be used as a starting point for the calculation of the work system value criteria and the comparative partial cost calculation. The calculation represents a central element of the evaluation system for CPPS. The second part of the research design focuses on the question of how variations of production systems can be created with the help of an automated design logic, building on established procedures for the design of assembly and manufacturing systems. For this purpose, the state of the art and science of design methods for CPPS will be examined again at the beginning and, also with the help of the selected Design Science Research Process model, a suitable design method will be selected from the already developed concepts and tailored to the specific use case of small batch production. As soon as the concept for the design of the production scenarios and their appraisal has been drafted, the actual design artefact is developed in the form of a prototype for the scenario configuration and the scenario comparison. For this purpose, different software applications are used, such as simulation software for occupancy planning and a calculation and data management tool for the calculation of costs and work system value criteria. Finally, the capabilities and limitations of the implemented prototype of a design and assessment assistance system are validated with the help of collected data in real assembly experiments at Werk150, the ESB Business School's learning factory on the campus of Reutlingen University.

1.7 Research methodology

Different requirements have played a role in the selection of the research methodology. One goal of the Engineering Management (and Digital Industrial Management and Engineering) study programme is to gain scientific knowledge that is close to application and, at best, to show industrial application potential. With Werk150, Reutlingen University, an industry-like research infrastructure is also available. For the present research work, which aims to develop a design and rating system for CPPS in the form of a digital twin, I have therefore chosen the Design Science Research Process Model according to Vaishnavi and Küchler, in which a design artefact or prototype is first developed abductively starting from a concrete problem and then tested deductively. (Vaishnavi and Kuechler 2004). The Design Science Research Process Model is explained in more detail in the following section.

1.7.1 Design science research process model

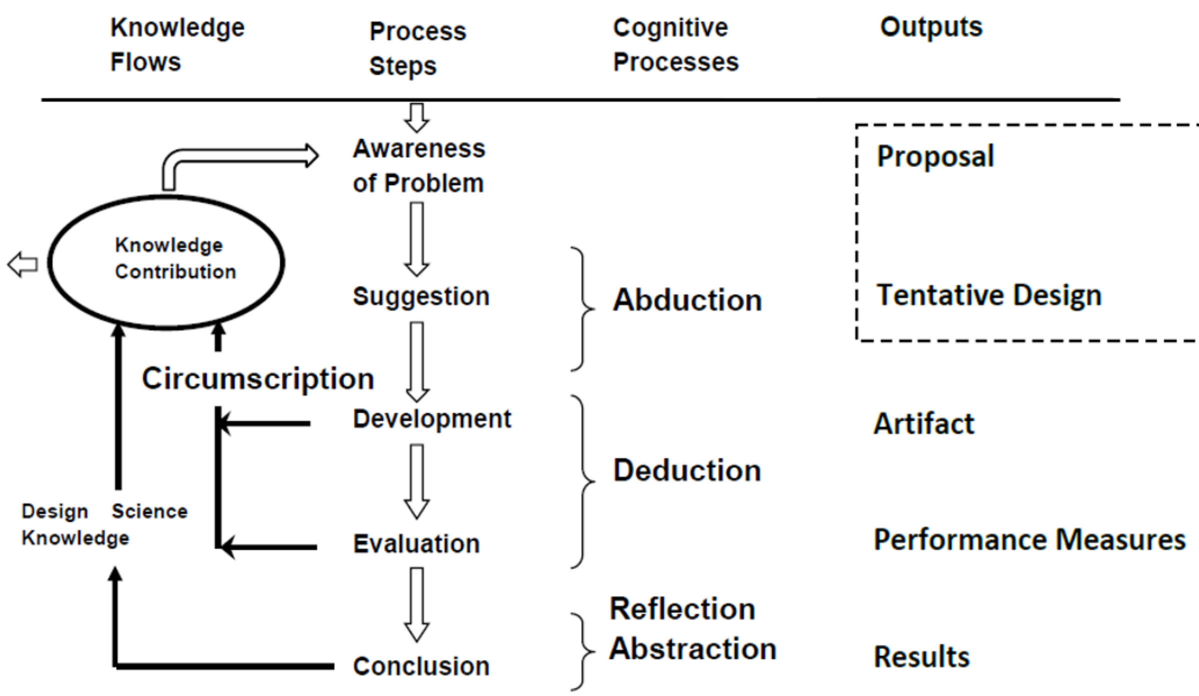


Figure 2: Design Science Research Process Model (Vaishnavi and Kuechler 2004)(Vaishnavi et al. 2019)

In the first step of the process model, an awareness of the problem is created. This is achieved mainly through a literature analysis in the areas of design and evaluation of CPPS, but also through direct communication with the supervising professors and lectures of the study programme. Based on the description of the research project (proposal), a first tentative design is created. This is then implemented as a prototype in the form of a so-called design artefact, with the help of assembly experiments in the Werk150 recorded data. The design artefact is the result of the abductive phase of the research. In the following step, the design artefact is validated deductively with the help of the data from Werk150 by analysing the simulation results. With the help of a deductive evaluation of the artefact and verification through expert review, the performances and limitations of the artefact can be determined. In the final conclusion, the findings are reflected and abstracted so that the research can contribute to scientific knowledge.

1.7.2 Analysis of literature

For the present work, the literature of different topics, such as the design of CPPS, as well as extended and classical economic efficiency calculation for production systems, is analysed. Two different approaches were taken. Firstly, a quantitative and semi-structured literature search was conducted on the search terms: CPPS, design of production systems, extended economic efficiency calculation, work system value and digital twin. The terms are searched for in both German and English through various channels. These include databases such as the Eddi Portal and the library at Reutlingen University, but also other databases such as Google Scholar and Research Gate. Renowned journals were also used, which can be identified with the help of journal ratings such as the VHB-Jourqual 3 sub-rating. Through the targeted search in journals, the quality and relevance, but also the conformity with the current scientific consensus of the papers can be ensured. The semi-structured search method means that the displayed texts are first restricted by title in order to avoid content that is irrelevant to the topic. Subsequently, the abstracts and summaries of the pre-selected articles, books and dissertations are read. Only texts that fit the research question and meet the quality criteria were read in full and included as a source of information in this research paper. The “CRAAP test", as described in the Research Online Course (Reutlingen University), helps to critically evaluate texts and provides the following five selection criteria: Currency (actuality), relevance (for my subject), authority (reliability of source), accuracy (Is the information reliable, truthful and accurate? This can be ensured by checking who is cited in the texts and whether academic or at least legitimate sources are used) and purpose (what is the information aimed at). The following table summarises the semi-structured method for searching and selecting texts, the information channels through which the sources are obtained and the search terms that serve as the starting point for the search.

Table 2: Semi-structured literature analysis (Reutlingen University; Kache et al. 2015)

Search method	Channels	Starting point
Semi-structured: Title → Abstract → Main text	**Databases:** - Reutlingen University Library/ Eddi Portal - Google Scholar - Research Gate **Esteemed journals**: - VHB-Jourqual3 and sub-ratings	**Search keywords**: - Cyber-physical production system - Design of production systems - Extended Economic Appraisal - Work system value - Digital Twin

1.8 Delimitations and limitations

This research focuses to develop a design artefact in the form of a systematic for configurating and rating alternative production scenarios. In this section the delimitations and limitation, of the research and the elements of the systematic, will be discussed. The systematic consists mainly of the elements of the checking for resource availability and employee assignment options, simulating and calculating costs and a work system value, which allow to facilitate decision making. The implemented scenario is used to continuously collect data, which enables a feedback and thus a comparison with the forecast of the planned scenario and improves the database over time. Creating the concept and a design artefact aims to present the functionalities and the coherency of the system and especially the calculation formulas for the work system assessment. The aim of this work is to develop a logic for the work system assessment that is coherent in itself and is finally implemented as a calculation tool. In the future, the aim is to collect big data with the help of continuous data collection and to be able to draw concrete conclusions about the quality of the forecast beyond the meaningfulness of the rating logic. The weak database, which results from the effort intensity of the full factorial design approach of the experiments, which will be explained later, and limited work power, only allows tendencies to be recognised for the concrete application example on the current status. This applies in particular to the recorded information on stress and error rate, which at the current stage do not allow statistically reliable findings on the prediction quality. For the other work system value criteria and costs, the simulation based on verified times provides the basis for the calculations. This aspect is conditioned by the time-limited framework of the research and barriers in the physical feasibility of production shifts for data collection. The abductive nature and interdisciplinarity of the research make it difficult to validate the design artefact developed. The applicability and transferability of the design artefact, literature and expert knowledge therefore serve as a means of validating the logic and system architecture. A model is a simplified image of reality that serves to represent the real functions as accurately as possible, but also in a usable way. The modelling framework for the scenarios, simplifies the real configuration possibilities and makes a clear distinction between either line production or single workstation, which in many cases cannot adequately describe industrial practice.

1.9 Thesis outline

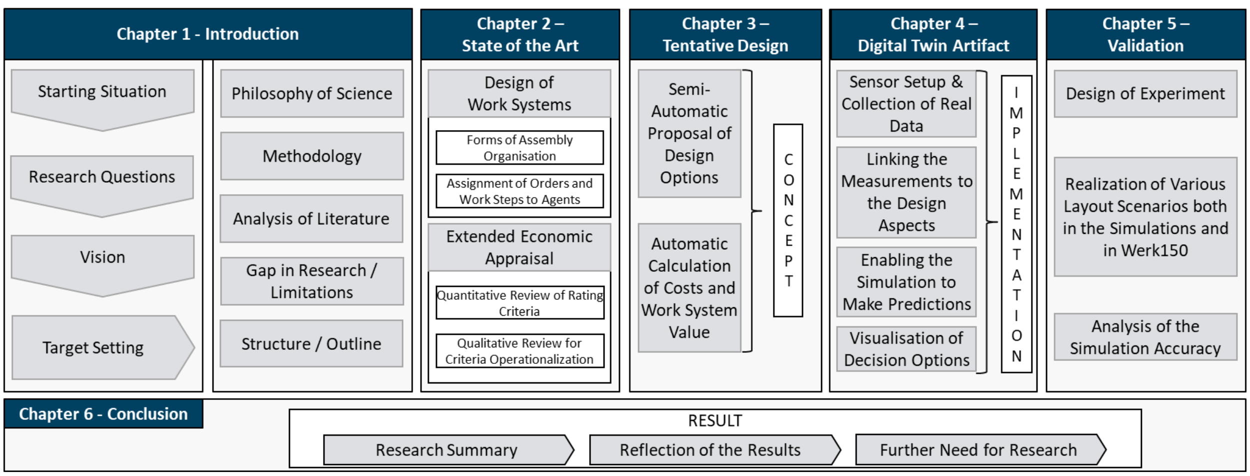


Figure 3: Thesis Outline

This thesis is divided into 6 parts. In the first part, introduction, the initial situation of the research and the guiding questions, as well as the vision and the concrete goals of the thesis are formulated. In addition, the preliminary considerations in the theory of science are presented. Alongside to the classification of the research in terms of philosophy of science, the methodology and the access to literature, as well as the research gap, the delimitation and the outline of the thesis are described. In the following chapter, the state of the art of the topics central to the research work, the design of cyber-physical production systems and approaches to extended economic efficiency calculation, are presented. The third chapter outlines the conceptual design of an artefact consisting of a rating system by means of EEA using a digital twin. In the fourth chapter, the concept is implemented as a prototype with the help of simulation software and a calculation tool. The development of the artefact as well as its validation is based on real measurement data collected in the learning and research factory of Reutlingen University, the Werk150. The experimental set-up of the experiments as well as the validation of the artefact are explained in the fifth chapter. In the concluding sixth chapter, the results of the research work are summarised and reflected upon, and open research needs are identified in order to contribute as much value as possible to the state of science with the help of the research conducted.

Chapter 2
Literature Review

This chapter provides an overview of themes in the literature that form the basis of this thesis. First, central terms are defined and areas of research are highlighted. The design of cyber-physical production systems, especially in the areas of work organisation and employee allocation, is discussed in detail. Furthermore, basics on economic efficiency comparisons are provided and extension approaches including possible assessment aspects are examined. Finally, the background to simulation and the digital twin is addressed.

2.1 Definition of terms and research fields

In the following section, central terms are first defined. Then, in Tables 3-5, an overview of the contents of representative literature works by various researchers is given, in which the central topic areas considered relevant for this research project are presented. This serves on the one hand to show the state of the art and on the other hand the focus areas and possible needs for research.

Cyber-Physical Production System (CPPS): Cyber-physical systems are more advanced mechatronic systems that serve as central enablers of networked production. Cyber-physical production systems result from the interconnection of multiple CPSs and form flexible and productive production networks. (Bauernhansl et al. 2016, 12). A cyber-physical production system, including possible elements and relations, is exemplarily visualised in the following graphic.

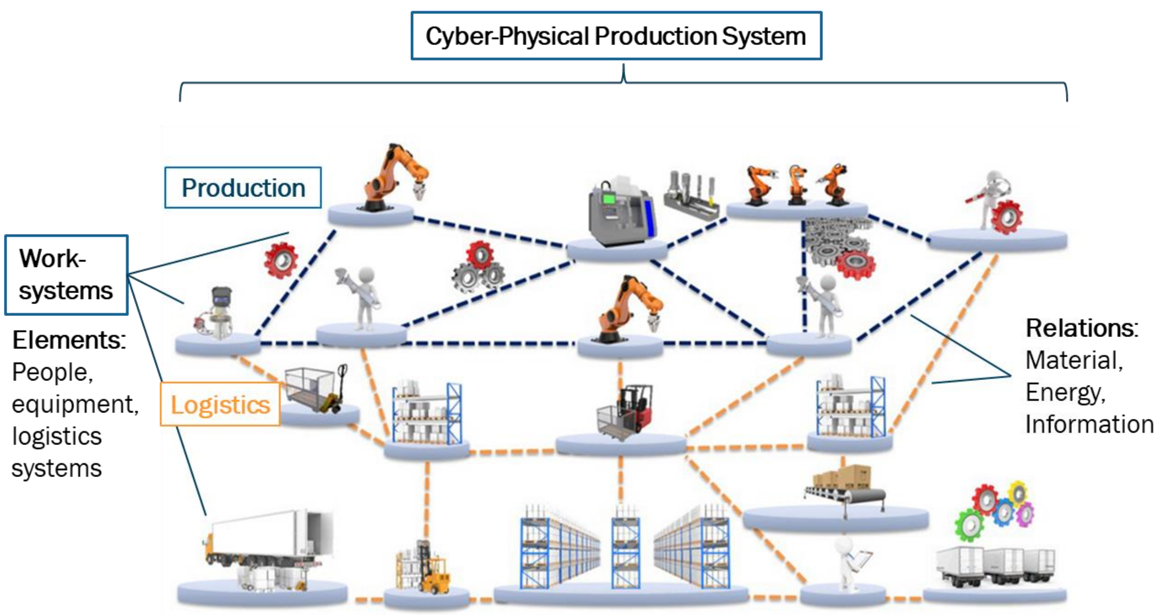


Figure 4: Cyber-Physical Production System

Digital Twin: Digital twins digitally map properties and states of real systems. They analyse the real system based on relevant data and models and return optimized data to the real system. (Langlotz et al. 2020, p. 343)

Extended Economic Appraisal: A method which attempts to break down the one-sided picture of human labour as a cost factor and draws attention to the medium and long-term returns that innovations in skills, health and improved work organization bring to the enterprise (Neubauer and Wächter 2011, p. 70).

Work System Value: The work system value expresses the quality of an alternative in terms of meeting non-monetary target criteria (Bullinger et al. 1993, p. 266).

Table 3: Research efforts and findings in the area of design and assessment of production systems I4.0 and CPPS

Design of Production Systems I4.0 and CPPS	Assessment of Production Systems I4.0 and CPPS
Method for the design of adaptable production systems – considers a systematic variation of factory structures and quantitative assessment of variants. Investment costs are not estimated (Löffler 2011)	
Methods, models, procedures for the dynamic design of complex production systems (Westkämper and Zahn 2009)	
Guidance to tailor methods for the implementation of a manufacturing system in the context I4.0 (Liebrecht et al. 2018)	Socio-technical assessment method with 30 criteria; comparison of existing assessment models for CPPS (Noehring et al. 2019)
Case studies from industry for the simulation-supported optimization of production and logistics processes (März et al. 2011)	Database acquisition for a simulation-based optimization of CPPS with a digital twin (Uhlemann et al. 2017)
Strategies of Production – Special aspects: Network design and adaptation; structural planning of networked productions; workplace design; digital, networked, versatile production (Westkämper and Löffler 2016)	

Table 4: Research efforts and findings in the area of EEA and work system value

Extended Economic Appraisal (EEA)	Work system value
Analysis of EEA methods, which balance rationality and humanity in a historical and current context (Neubauer and Wächter 2011)	Introduction of sub-areas of human-oriented work science. Description of assessment models (e.g. Hacker; Rohmert and Kirchner) and design approaches for work systems. (Schlick et al. 2010)
Shows application areas and limits of one-dimensional and multi-dimensional (diagnosis- and decision-oriented) extended efficiency appraisals. (E.g. Zangenmeister: 3-Step Model, Sengotta: Holistic procedure, Metzger: work system value appraisal, Picot/Reichwald: 4 Layer-model) (Ney 2006)	Factor analysis of 5 parameters using the example of a survey with administrators in the travelling postal service (Rohmert and Luczak 1975)
Calculation examples from industy for the consideration of rationality and humanity (Schultetus 2006)	Planning of assembly systems according to ergonomics/ work system value criteria at the production of Mercedes Benz AG (Bullinger et al. 1997)

Table 5: Research efforts and findings in the area cost accounting methods and work system value criteria

Cost Accounting Methods	Criteria of the Work System Value
Full-/partial costs calculation as decision basis in the context of technical development and production. The Partial cost approach is recommended for short-term decisions, in which direct costs and selected indirect costs are allocated directly and relevant overhead costs are added via an allocation key. (Schlink 2019)	Current efforts for sustainable development of companies from different cultural backgrounds presented in CSR Reports (Bosch GmbH 2018; Tesla AG 2019; Alibaba AG 2018)
	In-depth assessment methods for the quantification of flexibility parameters e.g. for Process-, Routing- and machine flexibility (ElMaraghy 2005; Wiendahl et al. 2007)
Process controlling using performance measurement systems to assess manufacturing costs and process costs: Presents a method, including examples, of calculating process costs based on time tracking as a foundation and using employee and machine cost rates (Grabner 2012)	Distinguishing between changeability and flexibility by visualizing the correlation between changeability and flexibility corridors (Fisel 2018; Foith-Förster et al. 2016)
	Detailed definition of different types of flexibility, such as Machine-, Routing-, Volume- and Process flexibility (Braglia and Petroni 2000; Müller 2016; Eicher 2020)
Lean Cost Accounting as an approach to expand the traditional accounting systems with decision relevant information which enable decision makers to take measures in the context of lean management (Maskell and Kennedy 2007)	Explanation of terms and relevance of Autonomy, Interaction, Collaboration in the context of Digital Twins as Socio technical Mediators (Cichon 2019)
	Creation of requirement profiles and individual competence profiles of employees with the help of the Code X Atlas (Faix 2012)
Static methods (cost comparison calculation, profit comparison calculation, profitability calculation and amortization calculation) and dynamic methods (asset value method and interest rate method) are used to calculate costs. In addition, single and multi-dimensional methods for extended profitability analysis are described (Ney 2006)	Norms for the specification of mental and physical workloads (DIN 33400; DIN EN ISO 10075-1 (2001))
	Measurable indicators with high correlation to (mental) load, such as heart rate and skin conductivity (Bartholdt and Schütz 2010; Böckelmann and Seibt 2011; Papaestefanou 2013; Boucsein 1992)

The tables 3-5 compile a cross-section of the state of the art and research efforts in the listed topic areas.

2.2 Design of cyber-physical production systems (CPPS)

The design of CPPS and production systems in general involves different elements. In the following, different possibilities for the division of labour and the resulting organisation forms and associated characteristics are described on the basis of a literature review. Subsequently, concepts for the allocation of agents to the work steps to be performed are presented. In the use case of scooter assembly in Werk150, employees serve as agents, i.e. operators who can carry out certain tasks, although this can also be substituted by robots and machines. Since this special use case is considered for the development of the design artefact, this section focuses on the assembly organisation, which can, however, also be extended to the production organisation.

2.2.1 Assembly organisation

"Assembly, in contrast to manufacturing, is characterised by relatively short execution times and the bringing together of several different objects to form a cohesive assembly or end product" (Wiendahl and Wiendahl 2020, p. 53).

2.2.1.1 Type division and quantity division

In order to understand the forms of assembly organisation, it makes sense to first look at the various concepts of division of labour. Division of labour, i.e. the distribution of tasks between actors in the production system, is essential for efficient production. A distinction is often made between type and quantity division. Type division is the division of a task into work steps and their allocation to different persons, each of whom is responsible for one work step of the overall process. With quantity division, on the other hand, all sub-steps of the product manufacturing process are carried out by one agent. This difference is clearly illustrated in the following figures.

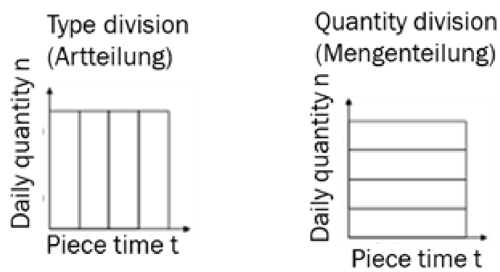


Figure 5: Type division and quantity division (adapted from (Siedenbiedel 2020))

In product manufacturing, there are many different concepts for organising assembly, which can be categorised by their degree of type and quantity division. The assembly organisation form of the individual workstation, where one employee individually manufactures an entire product, corresponds to the principle of quantity division. A production line in which the employees always complete the same partial work step at their workplaces, often at clocked times, and then let the product "flow" to the next place, on the other hand, corresponds to the principle of type division. These two forms of assembly organisation are complemented in practice by many mixed forms, such as semi-autonomous group work, in which employees support each other in their work steps as needed. The different forms of assembly organisation have different advantages and disadvantages, which is why the most ideal alternative can vary depending on requirements and framework conditions. Due to the increased efficiency with large quantities, Taylorism, i.e. an approach to production with a high degree of type division named after Frederick Winslow Taylor, has become established in industrial practice. The following diagram illustrates the basic principle of increasing efficiency through type division.

$$p_n = \frac{t_n}{t_t} \cdot 100\% = \frac{t_n}{(t_h + t_n)} \cdot 100\%$$

with
- t_n Secondary time in seconds [s]
- t_t Task time = Assembly time per piece in seconds [s]
- t_h Main time in seconds [s]
- p_n Secondary effort in relation to t_t in %

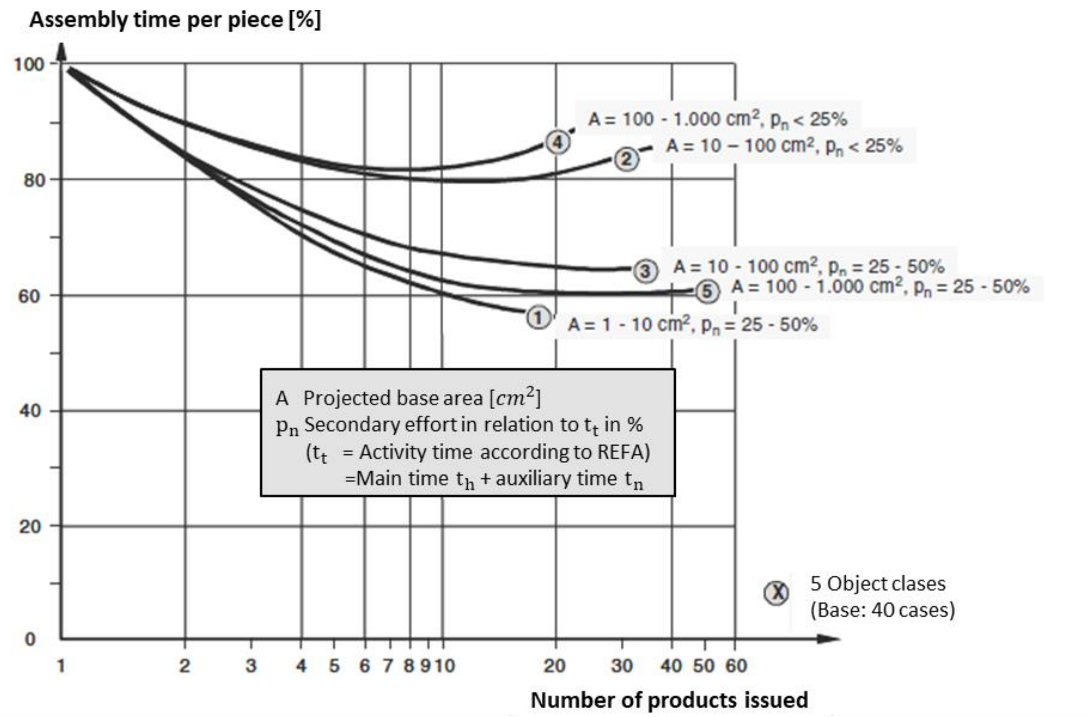


Figure 6: Assembly time as a function of the number of runs (Al-Kashroum) (Lotter and Wiendahl 2005, p. 135)

The repetition of movements in manual operations has an influence on the effectiveness of production. A task-based assembly with repetition of individual assembly operations requires less time than a piece-by-piece assembly. This is due to a lower impact of secondary operations, such as tool changes, or the grouping of repetitive operations, such as gripping small parts, and the specialisation of the worker to the operation. The figure by Al-Kashroum displays how the assembly time changes with the number of products manufactured. The diagram shows the results of an investigation about the impact of the projected base of a product, as well as the ratios between main time and auxiliary times on the assembly time per piece. For the activity time, the definition of the Association for Work Design, Company Organisation and Corporate Development (REFA) is referred to. For products with different projected base areas and ratios of main times to auxiliary times, the accelerations compared to batch size 1 are shown for different numbers of products output, i.e. repetitions. In the case of a base area of approx. $100cm^2$, the assembly time for a repetition number of 20 is only approx. 65% of the assembly time for batch size one (Lotter and Wiendahl 2005).

2.2.1.2 Forms of assembly organisation

In the following section, different forms of organisation and structuring principles for assembly systems are presented. Basically, the assembly tasks of products result from the structure of the products and the available assembly tools. A common planning aid for the resulting assembly steps is provided by activity graphs. Different structural forms can be used to perform the assembly tasks, which are related to the organisation of work (Lotter and Wiendahl 2005).

Line assembly (clocked line production)

In the assembly line, as in the production line, the overall task to be performed is distributed to different workplaces. It follows the order criterion of the work sequence and the line principle, in which one workstation is followed by another. The spatial structure and the form of organisation are visualised below (Wiendahl and Wiendahl 2020).

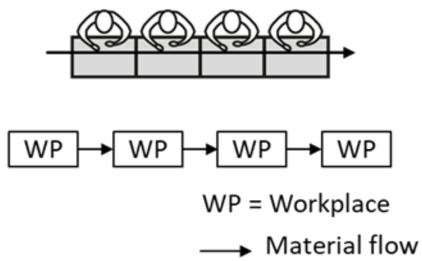


Figure 7: Line assembly (organisational form and spatial structure) (Wiendahl and Wiendahl 2020, p. 44)

For this purpose, the tasks to be completed are divided into sub-steps, which are then assigned to workstations arranged one behind the other. The respective employees thus focus on a subtask and pass the article on to the next workstation via a material flow system, where another employee continues the assembly process. Branching and parallel sub-steps are also possible. In order to avoid waiting times, synchronisation plays an important role in line assembly. This can lead to low capacity utilisation of individual stations. In addition, line assemblies as a whole system are susceptible to faults if an individual station fails. Further disadvantages are the low flexibility with regard to types, variants, output and the production process, and that even with extensive automation, cycle-related residual tasks remain. High operating and investment costs are also associated with line production. However, line structuring, with its clear material flow, short throughput times and low training times, offers good conditions for high quality, efficiency and automation, which has helped it to become widely used in industrial practice (Lotter and Wiendahl 2005).

Individual workstation assembly

In single workplace assembly, all the tasks to be performed, often complex ones, are done by one worker at one workplace. The organising principle is therefore the person working at a workbench. In the case of the individual workstation, due to the concentration of all activities at one workbench by one employee, all operating resources must also be available at one workstation. The individual workstation is often chosen for manual work (Wiendahl and Wiendahl 2020).

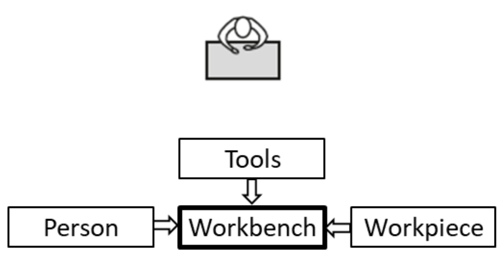


Figure 8: Individual workplace assembly (organisational form and spatial structure) (Wiendahl and Wiendahl 2020)

On the one hand, the need for all tools at one workplace has the disadvantage of high investment costs and lower utilisation of operating resources. On the other hand, a single workstation can easily be extended by an additional one, which brings relatively high volume-flexibility. Other flexibility characteristics, the low planning and control effort and the potential for individual employee performance development are also advantages of individual workstations. However, the volume output in individual workplaces is lower than in other structural forms, because the employee does not have to concentrate on a few repetitive work steps, but on many complex ones, which leads to a slowing down of the process time, as illustrated by Al-Kashroum. This also extends the training period and makes it difficult to implement single-user assembly for very complex tasks (Lotter and Wiendahl 2005).

Assembly island (semi-autonomous group production)

The assembly island can be seen as both a structural and organisational principle. Several employees work together on an assembly island where all operating resources are available at least once and complete several production or assembly steps in series or in parallel. The work can be done at one or more workplaces and follows the island principle (Wiendahl and Wiendahl 2020).

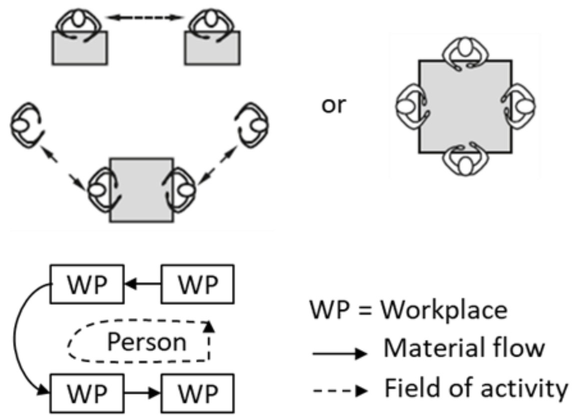


Figure 9: Assembly island (organisational form and spatial structure) (Wiendahl and Wiendahl 2020)

The special feature of this form of assembly organisation is the high degree of autonomy in the cooperation of the agents to fulfil the overall task. This brings with it a high degree of flexibility, but also an increased coordination effort. In this context, one also likes to speak of semi-autonomous group work, since several employees work together with a relatively high degree of freedom, which on the one hand leads to a high degree of flexibility, but on the other hand can also lead to fluctuations in production.

Construction site assembly

A form of organisation frequently used for large and complex products or, as the name suggests, for construction sites, is the construction site assembly. Here, the product to be manufactured is permanently assembled in one place and the employees as well as the equipment are mobile and work on the product with varying intensity. In construction site assembly, the product is the organising criterion and it follows the one-place principle or also called the construction site principle, when all work is carried out on and around a product that is difficult to move, such as a large machine (Wiendahl and Wiendahl 2020).

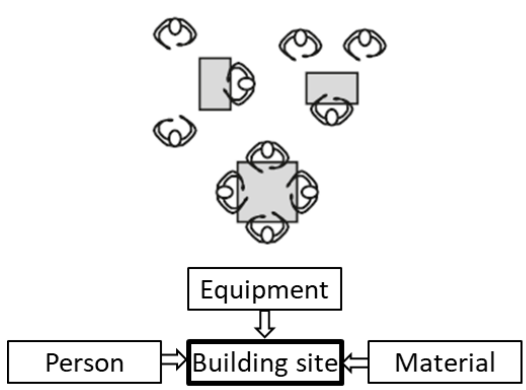


Figure 10: Construction site assembly (organisational form and spatial structure) (Wiendahl and Wiendahl 2020)

This form is particularly suitable for very large and complex projects due to its high flexibility and low planning and control effort. However, a high level of understanding of the product and its structure is required from employees. In addition, aspects such as the material flow, the space requirement and the long throughput times are reasons why this form of assembly organisation has not been able to establish itself in industrial series production (Lotter and Wiendahl 2005). In addition to the structural and organisational forms listed so far, there are other forms, such as automated assembly systems or hybrid assembly systems, which combine or extend characteristics of the forms already mentioned.

Table 6: Characteristics of Line, Individual Workstation and Semi-Autonomous Group Work (Grabner 2012; Thommen et al. 2020; Boeing; Dogan 2021; Sauer 2020)

Characteristic (Aspect)	Individual workstation					(Clocked) flow production – line assembly					Semi-autonomous group production - assembly island				
Principle	Point principle (centralisation of task/ execution)					Flow principle (object centralisation)					Group principle (combination of task and object centralisation)				
Author assessing the characteristic	Thommen	Grabner	Boening	Dogan	Sauer	Thommen	Grabner	Boening	Dogan	Sauer	Thommen	Grabner	Boening	Dogan	Sauer
Good plannability	○						●	●			●				
Low lead time			○		○		●			●	◕		◔		
High flexibility			●	●	●		○	○							○
Low stock levels & transport distances			○	○	○		◕				◕				●
Short changeover times			○					○			●		●		
Versatility of the work (e.g. strain)			●	●				○	○		●		◕		
High throughput (pieces per time)				○					●	●					
Easy Learnability of the work				○					●						
Good machine utilisation			○	○	○		◕				◕				●

Legend
According to author the characteristic is...
● ... fulfilled
◕ ... mainly fulfilled
◑ ... partially fulfilled
◔ ... hardly fulfilled
○ ... not fulfilled
Empty box: No statement was made

The table shown summarises the results of a literature research on the characteristics of the assembly organisation forms single workstation, clocked line production and semi-autonomous group production.

2.2.1.3 Employee orientation

The participation of people in the work process can take place in different ways, as described in the forms of assembly organisation, which can have an impact on the demands on employees and their opportunities for development. As Maslow suggests with his concept of the pyramid of needs (motivation pyramid), there are basic needs such as security and recognition, which can also be transferred to the world of work. As the fulfilment of basic needs increases, so does the need for aspects such as individual self-realisation. In the efficient division of labour as described by Frederick Winslow Taylor, employees are assigned to a precisely defined activity for a longer period of time. This leads to monotony, one-sided stress and limited learning opportunities. Needs for independence, self-realisation and identification with the activity can hardly be realised.

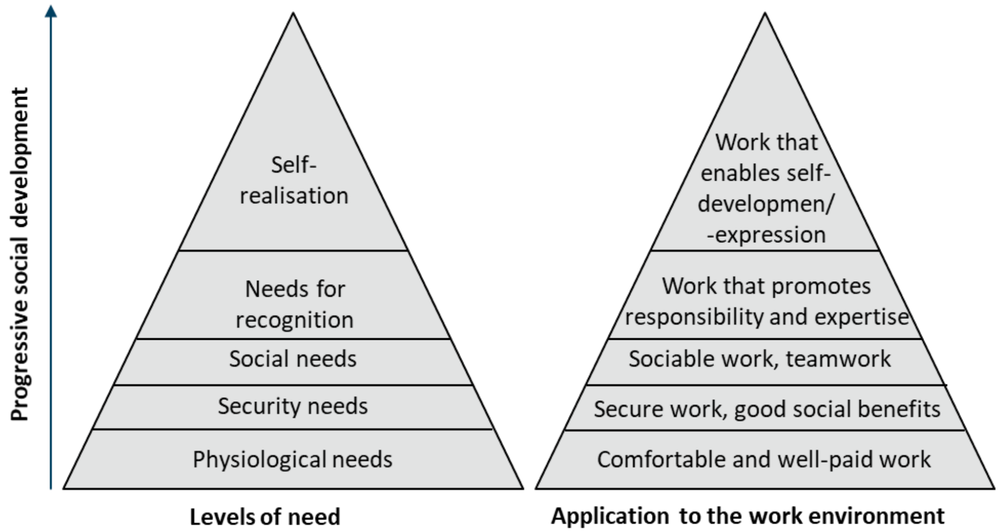


Figure 11: Motivation pyramid according to A.H. Maslow and its application to the work environment (Wiendahl and Wiendahl 2020, p. 56)

By working together with several people towards a common goal and through more diverse activity, these needs can be better met. There are different ways to break up the rigidity of production based on the division of labour, as visualised below.

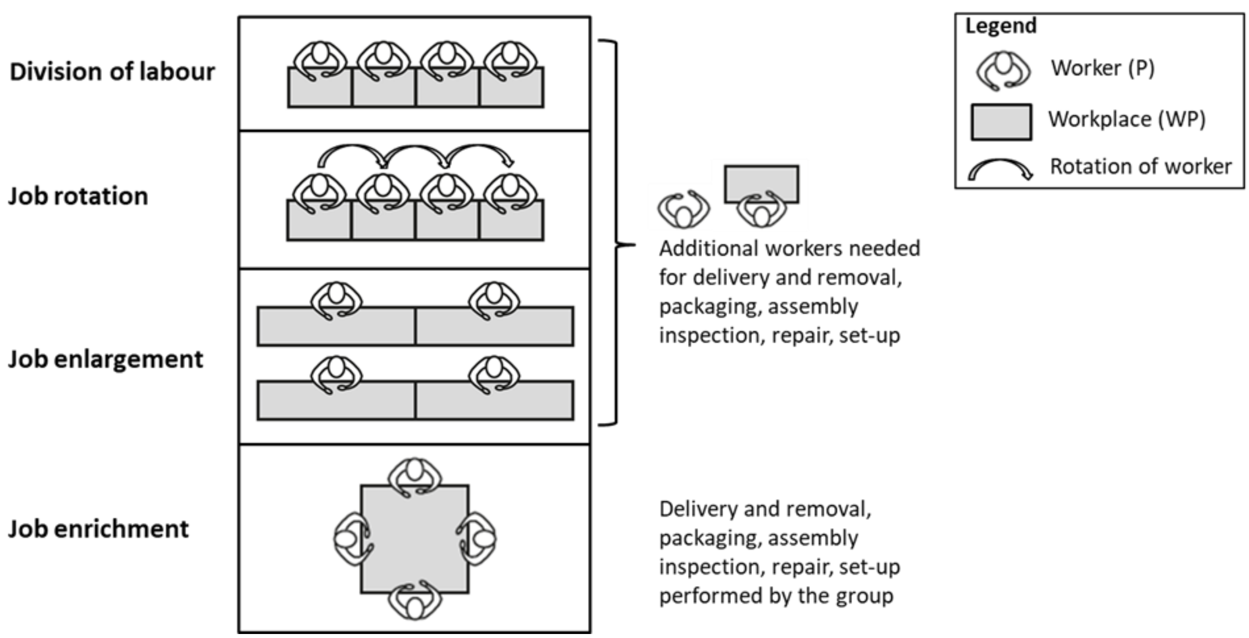


Figure 12: Concepts of division of labour, job rotation, job enlargement and job enrichment

In the case of job rotation, which is often carried out by so-called float employees or jumpers, several jobs can be performed by one employee, which reduces monotony and promotes product understanding. However, the qualification demand on the employee is also higher. In the case of job enlargement, several individual activities are combined to create extended tasks. The assembly organisation form of the single workstation represents the greatest possible job enlargement, as one employee performs all production steps independently. This increases job satisfaction, product understanding and identification with the product. Job enrichment goes one step further by transferring the directly and indirectly productive activities, including quality assurance and maintenance, to a work group that shares responsibilities in a self-organising manner. This comes closest to the concept of semi-autonomous group work, which meets the need for self-fulfilment as best as possible, but also places high demands on employee qualifications and the cohesion and motivation of the workforce, since both individual performance and the overall performance of the group can fluctuate and individual performance assessment is difficult (Wiendahl and Wiendahl 2020).

2.2.2 Assignment of agents to order related work steps

In the following section, some basic principles and concrete assignment concepts of agents to work steps are presented

2.2.2.1 Balancing

Despite the efficiency advantages of line production, it requires good synchronisation of the different partial activities in order to avoid waiting times of individual employees and stations.

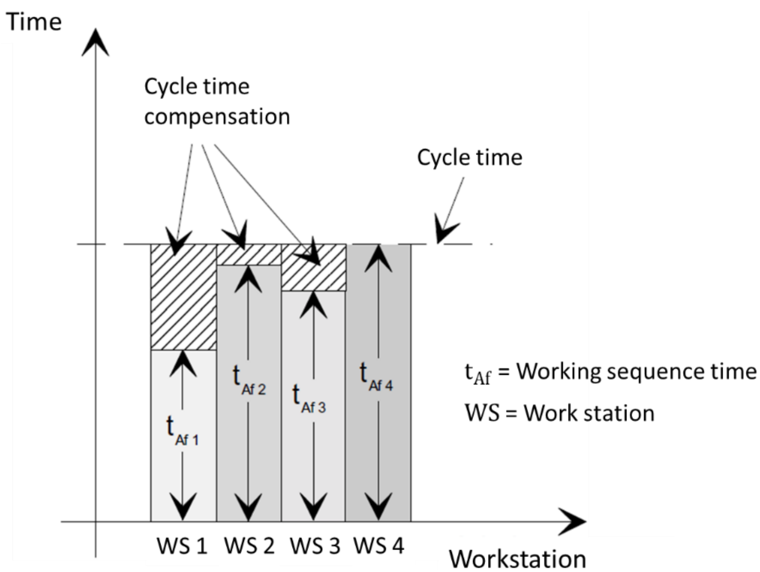


Figure 13: Clocking out (balancing) and occurrence of wasted times (Willnecker 2000, p. 123; Pröpster 2015)

Due to the threat of lost time in assembly based on division of labour, performance coordination (synchronisation) is of central importance. When adjusting the individual scopes, the precedence of the assembly processes must always be considered. The goal is that after successful synchronisation, the required assembly times of the individual stations correspond as closely as possible to the target cycle time. In reality, a complete coordination of performance is hardly feasible. This is why, for example, in assembly lines with division of labour, differences arise between the set-up time and the target cycle time, as shown in the diagram. An investigation by Schmidt (1990) in manual automobile assembly, for example, shows that the cycle compensation is 9%, which corresponds to a loss percentage that is tolerated in industry (Willnecker 2000, p. 123; Lotter and Wiendahl 2005).

2.2.2.2 Concepts for assigning agents to the task

For the allocation of tasks and the associated work steps to the available agents, the literature provides different approaches. The product, process, resources, skills (PPRS) model described by Herzog (2020) describes an allocation system of available resources to the skill requirements of the necessary manufacturing steps. On the one hand, a method of derivation is presented to establish assembly processes and the associated work steps from the product and finally to define capability requirements for each work step. On the other hand, the available resources are used to derive the available capabilities. The process model makes it possible to bring together the product and assembly requirements with the available functional groups and their capabilities. The following illustration briefly summarises the allocation method.

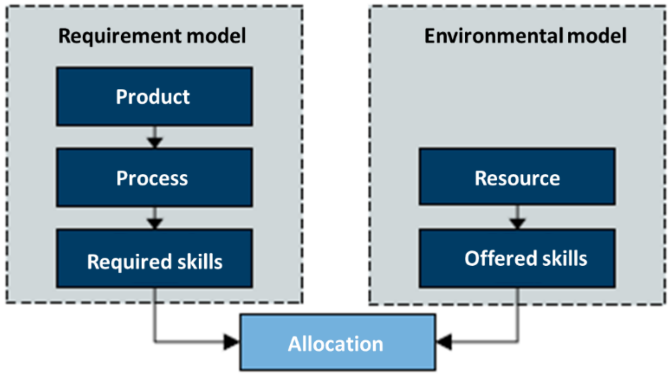


Figure 14: PPRS Modell for the automotive assembly (Herzog et al. 2020 - 2020)

Günthner and Tenerowicz (2011) describe an interesting concept for a modular and decentralised control of multi-agent systems in intralogistics, in which a logic is used for the selection of the best transport unit for each module according to order principle (Günthner and Tenerowicz 2011). A capability-based approach for the systematic allocation of subtasks between humans and machines in human-robot collaboration according to a better or worse principle for 25 different criteria is described by Ranz and Hummel (Ranz et al. 2017). Schröter (2016) also presents a similar approach. Among other things, he describes a capability indicator (f_K) for activity scheduling in order to facilitate the decision which worker to assign to which station (Schröter et al. 2016).

Table 7: Evaluation of technology aspects (Schröter et al. 2016)

Ordinal value	Capability of resource	Cardinal Value
Better	100%	1
Equal	50%	0.5
Worse	0%	0

$$f_K = \frac{t_c + c_i + \left(\frac{q_p + q_w}{2}\right)}{3}$$

Evaluation of cycle time: $t_c \in \{0; 0.5; 1\}$
Evaluation of additional invest: $c_i \in \{0; 0.5; 1\}$
Evaluation of process quality: $q_p \in \{0; 0.5; 1\}$
Evaluation of work quality: $q_w \in \{0; 0.5; 1\}$

Bruno and Antonelli (2018) presents a similar criteria-based task allocation procedure that provides guidance for human robot collaboration (HRC) allocations. It follows 3 steps. In the first step, task indicators are defined. They point out that the definition of indicators is a great challenge, because the indicators should be meaningful on the one hand, and on the other hand, they should also be easy to measure. In the second step, the work steps are divided into possible classes based on the indicators, which say by whom the activity can be fulfilled. Possible classes are: Human, Robot, Human or Robot, Human and Robot. The classification is done automatically by a classifier that uses a training set of data from past assignments. Finally, the assignment is completed using an "if, then" activity assignment flow chart (Bruno and Antonelli 2018).
Müller (2016) describes an approach with the principle agent theory, in which agents can independently offer themselves for work steps depending on their ability and availability.

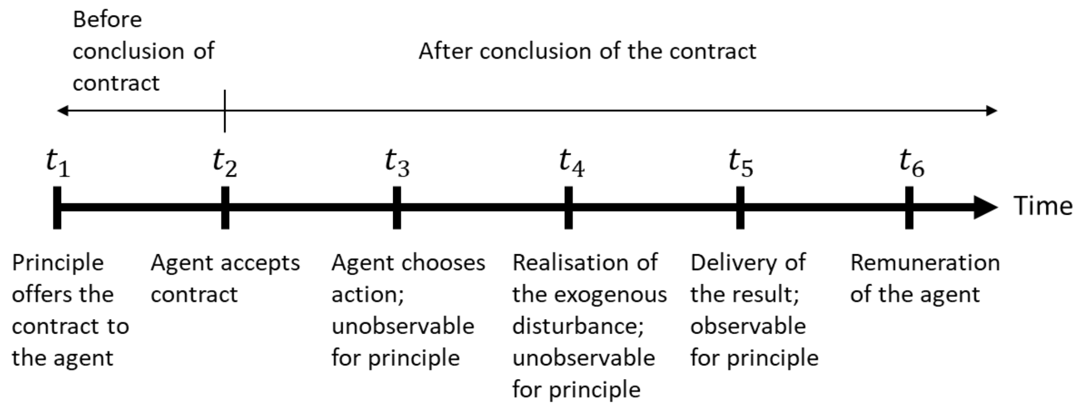


Figure 15: Timeline of a principal-agent relationship according to Ross (1973) (Müller 2016, p. 119)

As a use case for this type of task allocation in a principal-agent relationship, Xiong (2020) examines the compensation structure of the ride service provider Uber and Didi in China and reveals how a dynamic pricing system, taking into account local and current taxi conditions, is applied for driver rewards (Xiong et al. 2020).

2.3 Economic efficiency assessments and expansion approaches

Efficiency comparisons, usually in the form of cost accounting, are traditionally used to assess the economic efficiency of production scenarios. Different concepts and their fields of application are described below. The aim of this research work is to include aspects that are difficult to quantify. Different extension approaches can be found in the literature. Often, additional assessment dimensions are defined for important aspects. For this reason, difficult-to-quantify target aspects such as findings from work science and flexibility are addressed subsequent to the concepts of assessment extension.

Economic activity is a basic principle of companies that aims to convert the input, which usually consists of resources, as efficiently as possible into the desired output, which are often products. In order to assess the efficiency (quantitative economy) of an activity, the principle of economic efficiency is applied, which can exist in two different forms. The maximum principle tries to achieve a maximum output with a given input. The minimum principle, on the other hand, aims to achieve a defined output with the least possible use of resources. The relationship between input and output can be illustrated with the help of a production function (Schlink 2019).

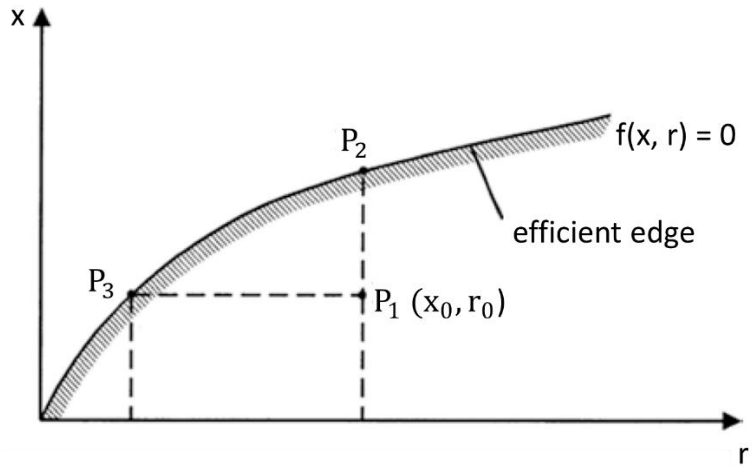


Figure 16: Production function to illustrate the maximum and minimum principle (Schlink 2019)

The illustration shows a simplified system with only one resource type r and one product x. Theoretically, all combinations below the line are possible, but they would be inefficient because the maximum productivity is not achieved as in P_1. Productivity is defined as the quotient between quantitative input and output and thus describes the efficiency of production. If the production quantity x_0 is given, the most efficient production is achieved at P_3, which corresponds to the minimum principle, and if the resource input r_0 is given, the highest productivity is achieved at P_2, which corresponds to the maximum principle. P_2 and P_3 are on the efficient edge and can thus be considered efficient. In addition to the quantitative economic efficiency analysis, a value-based interpretation of economic efficiency serves to facilitate the assessment of economic action. When considering resources, their costs are also considered. The prices in connection with the quantities of resources consumed are the costs of production. Which resources are included in the consideration depends on the objective of the consideration and leads to different methods of cost accounting. Since the cost types all have the same unit, the value-based view facilitates the profitability comparison. In principle, the aim is to achieve maximum revenue (or, depending on the term, turnover or sales revenue) with minimum costs. The minimum and maximum principles also apply here and can be described as cost minimisation or revenue maximisation. In practice, formal economic target figures have become widespread and are, for example, the basis of the targets to be defined and the annual financial statements, i.e. the figures from the balance sheet and income statement- targets can be, for example, profit, growth, return on equity or securing existence, resulting in maximising shareholder value or earnings (e.g. dividends) (Schlink 2019).

Sengotta et al. (1997) have categorised target criteria for the decision between investment alternatives and distinguishes between monetarily quantifiable and non-monetarily quantifiable aspects. They further divide the monetarily quantifiable ones into directly monetary characteristics, such as profit or inventory, and indirectly monetary aspects, such as capacity utilisation or error rate. On the other hand, the characteristics that are not quantifiable in a monetary sense are subdivided into qualitative aspects, such as reputation or culture, and quantitative aspects, such as flexibility, workload or qualification. The following overview shows the distinction with examples of target criteria.

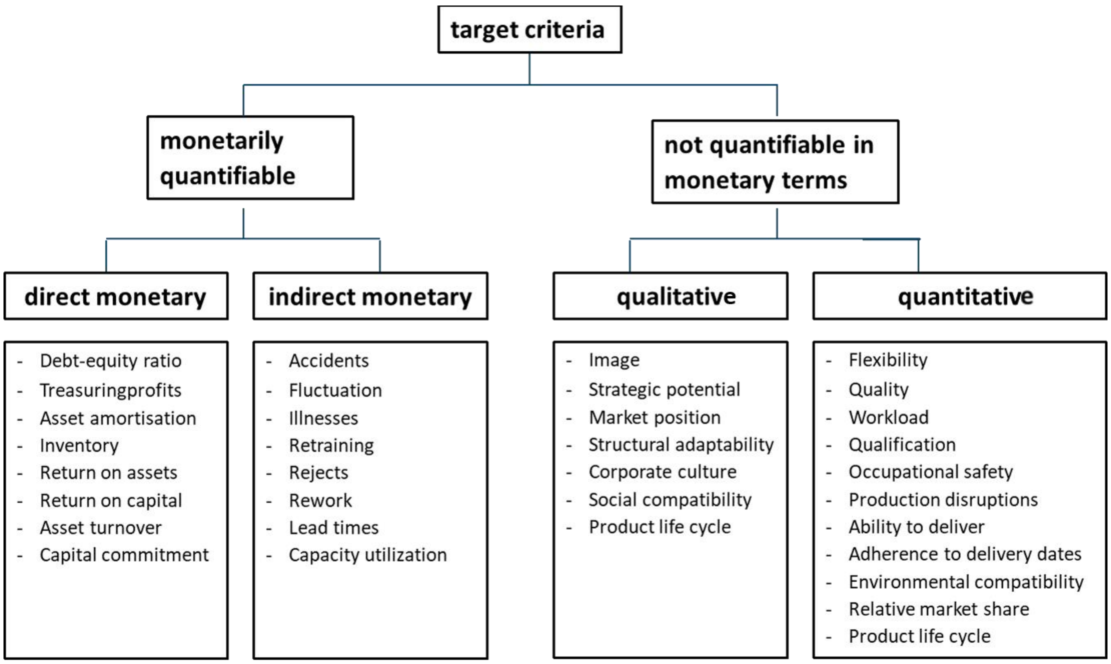


Figure 17: Categorisation of target criteria of an investment decision (Sengotta et al. 1997; Ney 2006)

The following figure gives an overview of economic efficiency comparison methods, including extension approaches that go beyond a cost comparison. Economic efficiency analyses generally aim to estimate the effects of an investment. In practice, not only the quantifiable, monetary values play a role in the decision-making process, but also other resources and objectives that a company is pursuing.

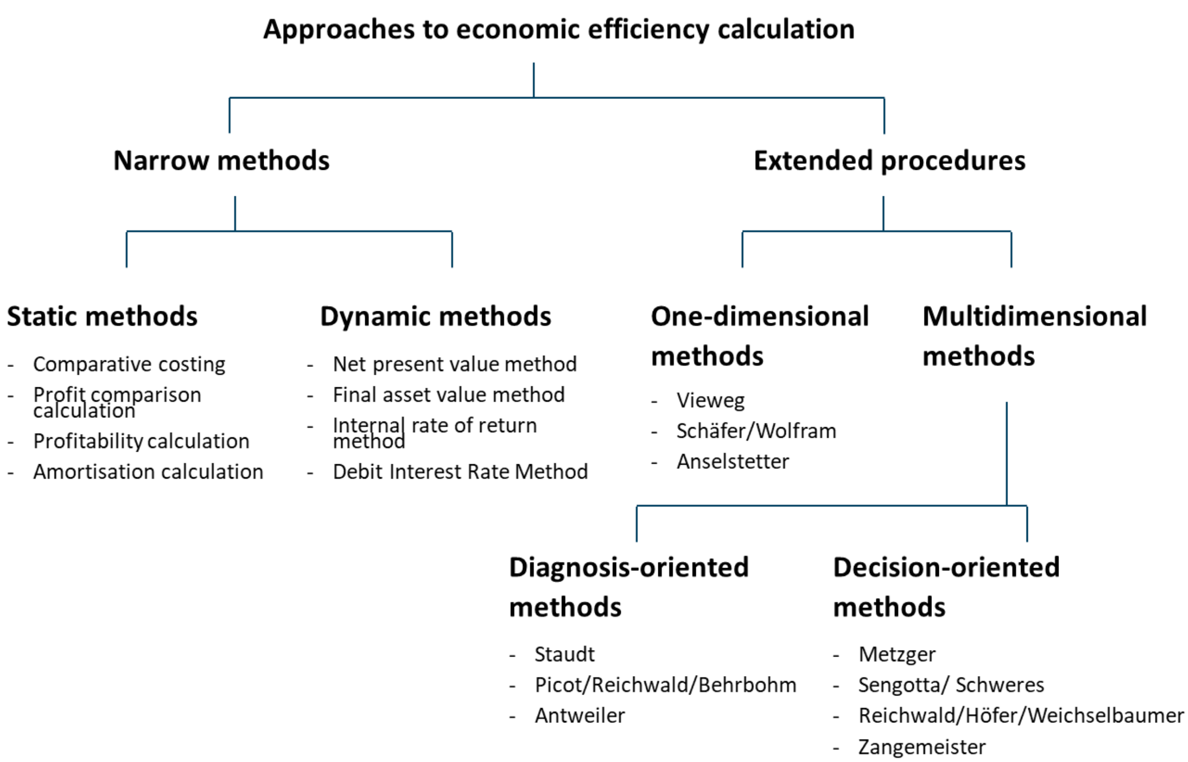


Figure 18: Approaches to economic efficiency calculation (Reichwald et al. 1996; Ney 2006)

Zangemeister (2000) categorises different procedures according to scope, i.e. whether the consideration is limited to an isolated area of influence or whether additional compound effects also play a role. The categorisation dimension of organisation refers to the groups that are integrated into the assessment process and how required information is gathered. Finally, dimensionality is an aspect of differentiation that describes the type of measures considered and whether any qualitative and quantitative effects can be included in the procedures. Narrow procedures are characterised by low scope and flat organisation. Extended procedures try to break this up. Extended procedures include the one-dimensional procedures, in which only monetary aspects are considered, but the scope is extended to upstream and downstream areas of the process chain. The multidimensional procedures allow effects with different dimensionality to be considered, both qualitatively and quantitatively. A distinction can be made between diagnosis-oriented and decision-oriented procedures. Diagnosis-oriented means that summarised justifications or argumentative explanations of relevant effects of a project are presented and offer the decision-maker a condensed information basis. Decision-oriented procedures, on the other hand, formalise the condensation of information with the help of a calculation, which supports the decision-maker in assessing the target criteria. Static and dynamic methods belong to the narrowly defined methods. Static procedures refer to periodized performance indicators. This includes the cost comparison calculation, which assesses the advantageousness of an investment alternative according to the lowest costs and does not take the revenue side into account. Profit comparison calculations instead consider not only costs but also revenues (profit = revenues - costs). The profitability calculation also makes it possible to take the capital employed into account in the calculation. In contrast to the calculation methods mentioned above, an amortisation calculation considers the cash inflows and outflows of a project. The decisive factor is the number of periods it takes until the returns of a project cover the acquisition costs and thus amortise them. The dynamic methods, which are also referred to as financial mathematical methods, consider several periods, the inflows and outflows, as well as an interest factor. One of the dynamic methods is the asset value method, which estimates the change in assets over the planning horizon with a fixed interest factor. In the net present value method, the payments refer to the beginning of the period (discounting), whereas in the annuity and asset value methods, which include the interest rate method and debit interest rate method, the payments refer to the end of the period (compounding) (Ney 2006).

Costs can be divided into different categories. A distinction is made between fixed and variable costs according to the production quantity, between full and partial cost accounting according to the decision to be made, and between actual and planned costs according to time. In terms of allocability, a distinction is made between direct and overhead costs. Costs are generally the assessed consumption of resources caused by the production process in an accounting period. The causation principle, which addresses the production reference of costs, provides causal and final interpretations that form the basis for short-term and long-term decisions and the concepts of variable and fixed costs. Fixed costs are incurred through investment in production readiness and variable costs for the production of products. Another aspect of cost accounting is the time reference, i.e. the period for which they are calculated. A distinction is made between actual and target costs. The total costs are classified according to allocability. Costs can, for example, be clearly assigned to a product, an order. The individual costs (direct costs), such as wages, material, in addition to the overhead costs (indirect costs), such as rent, machines and the special individual costs, such as tools or commission, form the various cost types. In order to be able to allocate overhead costs to individual products, a source-related distribution/allocation key (costing rate) is needed. If the total costs of the enterprise are distributed to the manufactured products, this is called full cost accounting. If only a part of the total costs is distributed, this is partial cost accounting. If, for example, a short-term acceptance of orders or the comparison of orders within a short time horizon is to be weighed up, variable costs (partial costs) are normally predominantly relevant, since only these are additionally caused. If it is a short-term decision and the production capacity (production readiness) is not affected, most fixed costs are irrelevant to the decision and partial cost accounting should be the basis for the decision. For long-term decisions that influence the readiness to produce, full cost accounting is useful. In this research work, looking into the near future, the variable costs and parts of the fixed costs are considered, which differ between configurated scenarios (Schlink 2019).

Extended economic efficiency procedures comprise a large number of procedures that often differ from each other only in minor details. Therefore, the procedures considered relevant for this work will be discussed in more detail. As already mentioned, the extensions refer to the three characteristics of scope (focus on an investment area or system-related), organisation (department-specific or company-wide and integrated) and criteria type (one-dimensional or multi-dimensional). In particular, the extension of the type of criteria leads to multidimensionality and can be seen as the most important feature in terms of content and evaluation methodology. The focus is enabled on further relevant effects and also non-monetary, qualitative and quantitative criteria can be included. Since the target criteria considered are heterogeneous, a purely financially analytical aggregation is not possible, which leads to an aggregation problem. From this challenge to include different effects, methodological approaches have developed in order to be able to make an overall statement about the advantageousness of the costs and benefits.

According to Zangemeister, four different approaches can be used to aggregate multidimensionality. The financial-analytical approach monetarises all effects for an investment calculation, which, however, limits the method to monetisable aspects, as in the case of narrowly applied procedures. The argumentative approach presents strengths and weaknesses verbally or qualitatively and delivers as a result a tabular multi-dimensional information basis without the aggregation of ratios. Utility analysis approaches "analyse a set of complex alternative courses of action and arrange them according to decision-maker preferences in a multi-dimensional target system" (Zangemeister). Quantities of different dimensions are first made comparable in a transformation step by ranking them on a dimensionless ordinal point scale. Finally, a value synthesis is carried out to condense the information by adding the weighted point values of the criteria. The cost-effectiveness analysis approach enables a comparison of the multidimensional (non-monetary) effectiveness with the monetary use of resources, i.e. a relationship between target effectiveness and costs. On the input side there is a monetary cost calculation, such as a classical investment calculation, and on the output side a preference-determined utility analysis. Combinations of the methods presented are easily possible. Since countless concepts for economic comparison are discussed in the business management literature, this research work will go into detail on the approaches that are considered relevant. The focus is on the basic principles and their exemplary presentation with the help of various example approaches that extend cost accounting by a work system value determination, i.e. of decision-oriented cost and effectiveness analytical procedures (Ney 2006).

Schultetus shows a possible approach to evaluating alternatives for a project. He distinguishes between the main criteria of rationality, which refers to economic effectiveness and efficiency, and humanity, which is people-related. He then defines sub-criteria that should be included in the analysis (Schultetus 2006).

Criteria		
Main criteria	Rationality (effectiveness and efficiency)	Humanity (promote people and not overstrain them)
Sub criteria	physical stress, mental stress, occupational safety (frequency of accidents, risk potential), environmental conditions, employee satisfaction, absenteeism, customer satisfaction	

Figure 19: Calculation of the work system value using main and secondary criteria (Schultetus 2006)

Metzger's (1977) approach very clearly describes the basic idea of a cost and effectiveness analytical approach, which serves as the foundation of many procedures and has not changed in essence over time. The idea is on the one hand to carry out a comparison of economic efficiency, often in the form of a cost or profitability calculation. In the analysis, preparation costs, job repetition costs, implementation costs and other costs are calculated on the input side. In addition, an extended utility value analysis is carried out in parallel on the output side, which looks at both technical and personnel aspects and forms the work system value (Ney 2006).

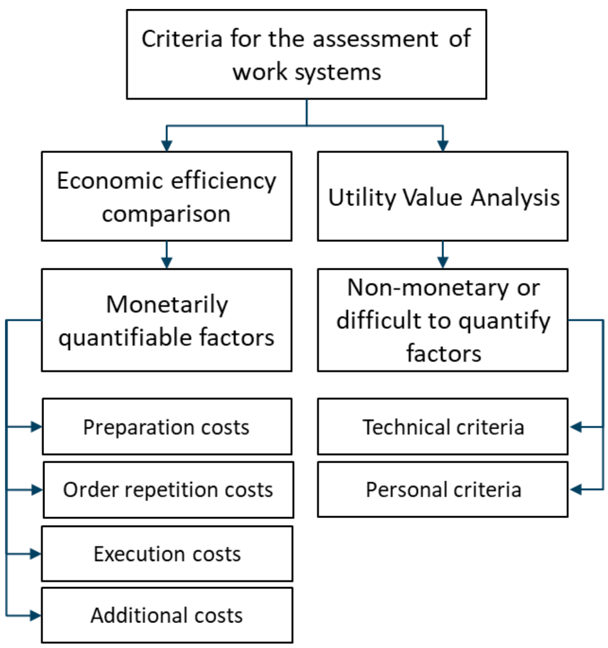


Figure 20: Criteria structure of work system assessment according to Metzger 1977 (Ney 2006)

The following equation is used to calculate the utility value side of the calculation, which is used in decision-oriented procedures to formalise information compression of criteria that are difficult to quantify.

$$\text{Utility Value} = \sum_{i=1}^{m}[g_i * n(k_i)]$$

g_i	=	Weighting of the target criterion
k_i	=	Characteristics of the target criterion
$n(k_i)$	=	Transformation function for the target criterion
m	=	Number of criteria

Figure 21: Utility value analysis with transformation and weighting of target criteria as the basis of the work system value calculation (Ney 2006)

As already described, when calculating the utility value, the properties of each target criterion are first made comparable with the help of a transformation function. This is usually done by ranking or transferring them to an ordinal scale. A sector diagram, as shown in the following diagram, is a good way of visualising the equation. It represents the degree of fulfilment of each criterion by the length of the circle sectors and the weighting of the criteria by the width of the circle sectors. The dashed circle represents the resulting work system value. The diagram is characterised by good clarity and high information content and thus allows a detailed insight into the advantages and disadvantages of the evaluated alternative, which is no longer visible by merely calculating the work system value.

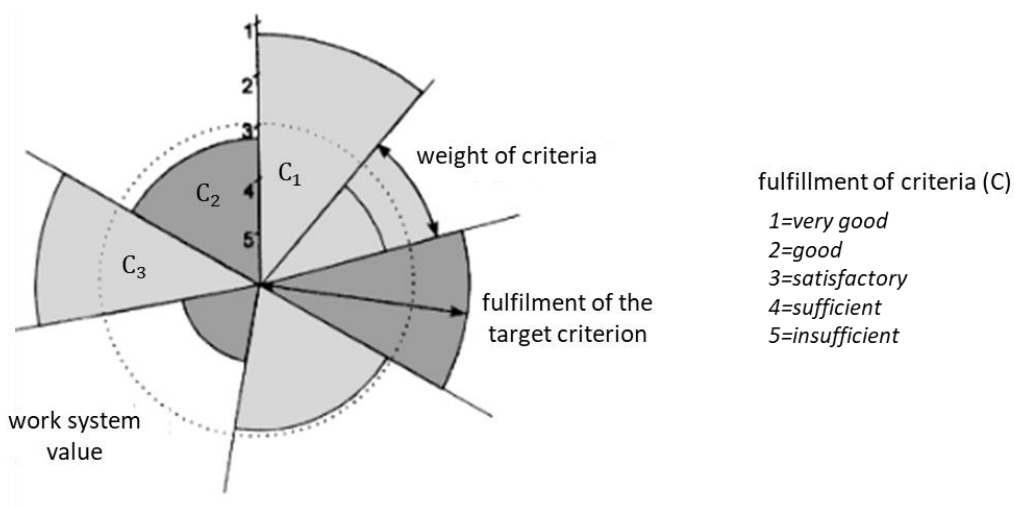


Figure 22: Principle of the circle sector diagram (Frauenholz et al. 2000)

The holistic calculation procedure for investment planning (GRIP) by Sengotta and Schweres (1994) is based on the utility value analysis by Zangemeister (1971) and takes up the concept of Metzger (1977), but takes cost accounting as a given and therefore does not go further into the cost side of the consideration. In the actual implementation of the procedure, 4-8 people from different departments agree on a catalogue of relevant criteria, which is elaborated in the form of a criteria tree. At the lowest level of this list, each aspect is classified according to school grades (German grading scale) (Frauenholz et al. 2000).

The individual ratings are aggregated for each criterion and a weighting assigned. The following shows the principle of work system value determination and visualisation with concrete target criteria

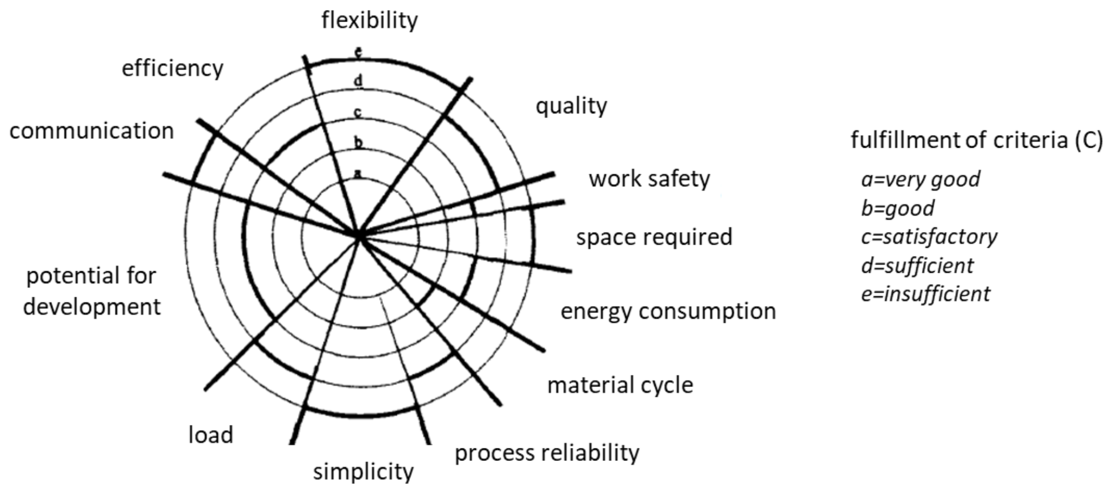


Figure 23: Circle sector diagram for the representation of target fulfilment with concrete criteria (Sengotta and Schweres 1994)

Bullinger (1997) follows a similar procedure in determining an economic value for the work system evaluation of different forms of assembly organisation. The criteria he chose are shown below.

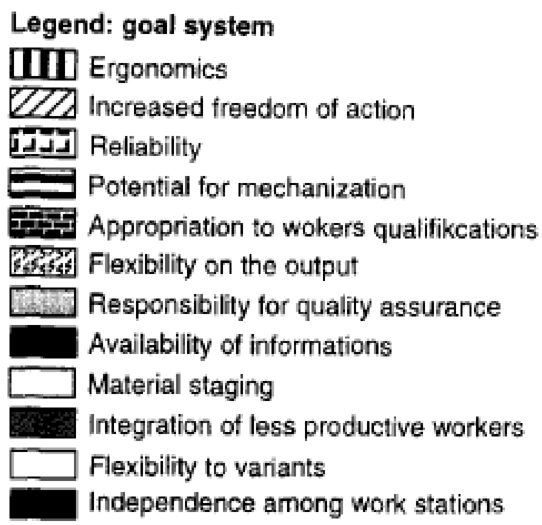


Figure 24: Goal system for the determination of econimic value (Bullinger et al. 1997)

Wulf and Nyhuis (2008) describe an evaluation system for different planning element combinations. The benefits are selected from a catalogue and rated by experts for each planning element combination on an ordinal scale of 1 - 5 and given a feature weighting so that an overall score is calculated. In the example, they apply the following characteristics: Cost, Performance, Adaptability, Sustainability, Lead Time, Delivery Reliability and Employee Qualification. The final score of the benefit evaluation is given as a percentage and enables an overall evaluation of the scenario and a ranking of the alternatives, taking into account company-specific KPIs (Wulf and Nyhuis 2008).
Wiendahl (2020) describes an approach that is strongly oriented towards the variation of the manufacturing organisation form and an extended economic efficiency approach with the help of the work system value. The differences in the work systems result from the arrangement of people, workpiece carriers, conveyor lines and storage. For each scenario, a material-related and a person-related work system value is compared with the costs (Wiendahl and Wiendahl 2020).

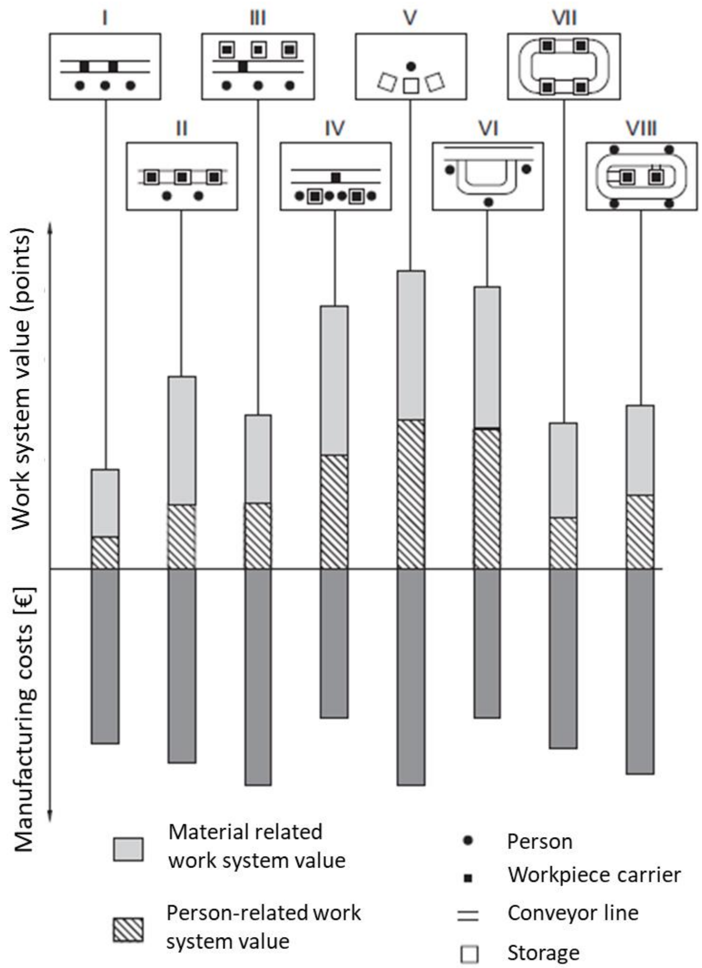


Figure 25: Comparison of work system values and costs of alternative work systems (VDI) (Wiendahl and Wiendahl 2020)

Keuntje (2019) presents a 4-step process in which the planning task is defined in the first step and then different planning variants are created. These are then dimensioned by checking the technical feasibility, resources and times. In the final step, the planning variants are evaluated with the help of a profitability calculation based on investment costs and project costs as well as with the help of non-monetarily quantifiable aspects. An overall score is determined for each planning variant (Keuntje 2019).

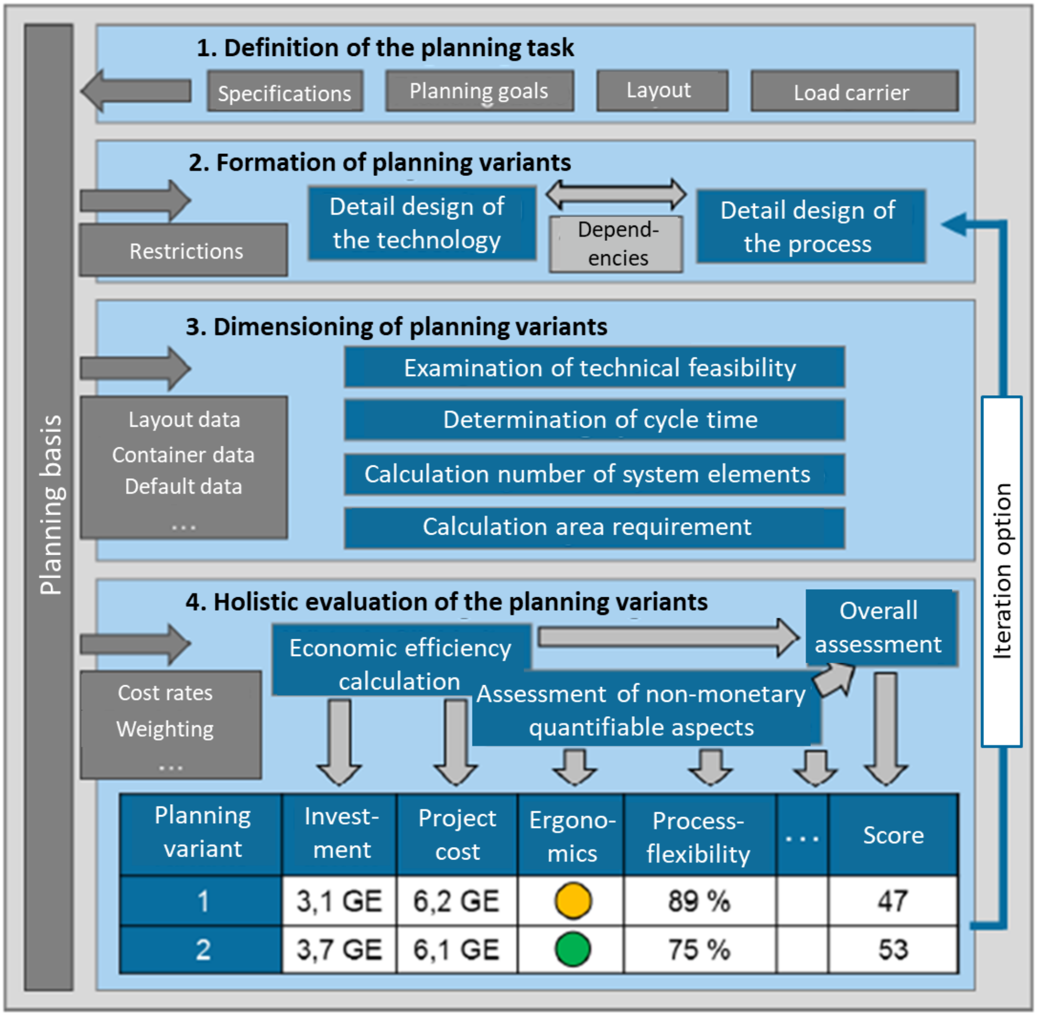


Figure 26: Overall concept of the procedure methodology for the integrated detailed design technology and process of route train systems (Keuntje 2019)

In the work system value calculation, the fulfilment of the advantageousness of an investment alternative is evaluated. For this purpose, the objectives of the enterprise are defined in the form of criteria. The concepts described so far already provide good indications of the desired effects of a project. However, since many concepts were developed several decades ago and the target systems vary depending on the project and institution, research was carried out to find current targets in institutions. Sustainability goals or Corporate Social Resposibility (CSR) efforts can provide an indication of possible desired goals of a company. The following is a brief overview of different companies and institutions from different cultural backgrounds to give a first indication of possible target effects. Corporate Social Responsibility is a "concept that serves as a basis for companies to integrate social and environmental concerns in their business activities and in their interaction with stakeholders on a voluntary basis" (KOMMISSION DER EUROPÄISCHEN GEMEINSCHAFTEN 2001).

Table 8: CSR strategies of different institutions

Institution	CSR strategy
UN Global Sustainable Development Goals	1: No Poverty; 2: Zero Hunger; 3: Good Health and Well-being; 4: Quality Education; 5: Gender Equality; 6: Clean Water and Sanitation; 7: Affordable and Clean Energy; 8: Decent Work and Economic Growth; 9: Industry, Innovation and Infrastructure; 10: Reduced Inequality; 11: Sustainable Cities and Communities; 12: Responsible Consumption and Production; 13: Climate Action; 14: Life Below Water; 15: Life on Land; 16: Peace and Justice Strong Institutions; 17: Partnerships to achieve the goal
DIN ISO 26000 Bundes-ministerium Arbeit und Soziales	7 Principles: 1: Accountability (for effects on the economy, environment, society), 2: transparency, 3: ethical behavior, 4: respect for the interests of stakeholders, 5: respect for the rule of law, 6: respect for international standards of conduct, 7: respect for human rights 7 Key Topics: 1. Organizational governance, 2. fair business and operating practices, 3. human rights, 4. consumer concerns, 5. labor practices, 6. environmental integration and development, 7. community
SAP (Website)	Powering opportunity for all people through digital inclusion initiatives; Environmental, social, and economic sustainability; Human Well-Being
Tesla (CSR Report 2019)	Environmental impact (battery recycling, NOx, water, energy); product impact (usefullness, safety, disaster relief, resilience of the grid); supply chain (responsible resource sourcing); people and culture (safty for employees, ergonomics, individual rewards, culture of diversity and inclusion, workforce development, community engagement, employee mobility and transportation)
Alibaba (CSR Report 2018)	Sustainability priorities: corporate governance (e.g. ethical conduct, social responsibility, leadership: integrity, intellect, emotional intelligence, ethical conduct, energy, ability to influence, strategic mindset, open-mindedness, resilience, self-awareness, and humility), intellectual property rights protection (trust), cybersecurity, data protection, human capital, social impact, enviromental impact

2.4 Further aspects of work system assessment

The following section discusses in detail work system aspects that are considered relevant to work system assessment alongside monetary issues

2.4.1 Changeability of the factory and flexibility corridors

In order to adapt to long-term trends and shorter-term turbulence, the ability to change is desirable for production systems. Since system adaptations vary in scope and depth depending on the level of the production performance unit and the market performance unit, different terms have developed to differentiate them. The following illustration clearly describes conceptual differentiation possibilities.

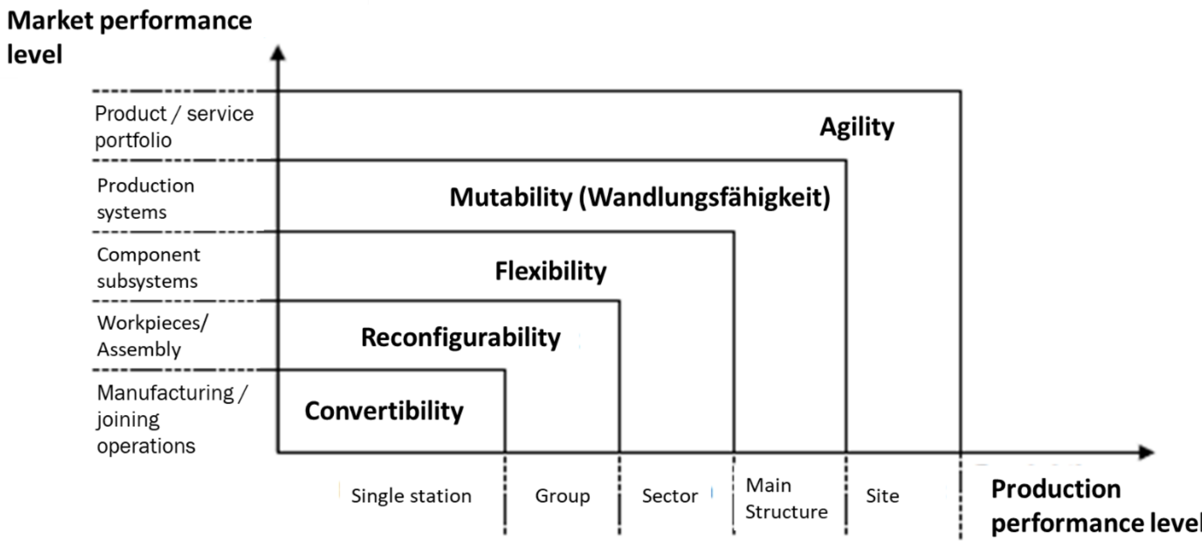


Figure 27: Shell model for variability in the factory (Eicher 2020)

A helpful distinction, simplified by this model, can be made between flexibility and adaptability (Wandlungsfähigkeit). The diagram visualises the basic relationship of the more short-term flexibility and the far-sighted adaptability, both of which are demanded by internal and external influencing factors. The flexibility corridors indicate the limit ranges for system adaptation.

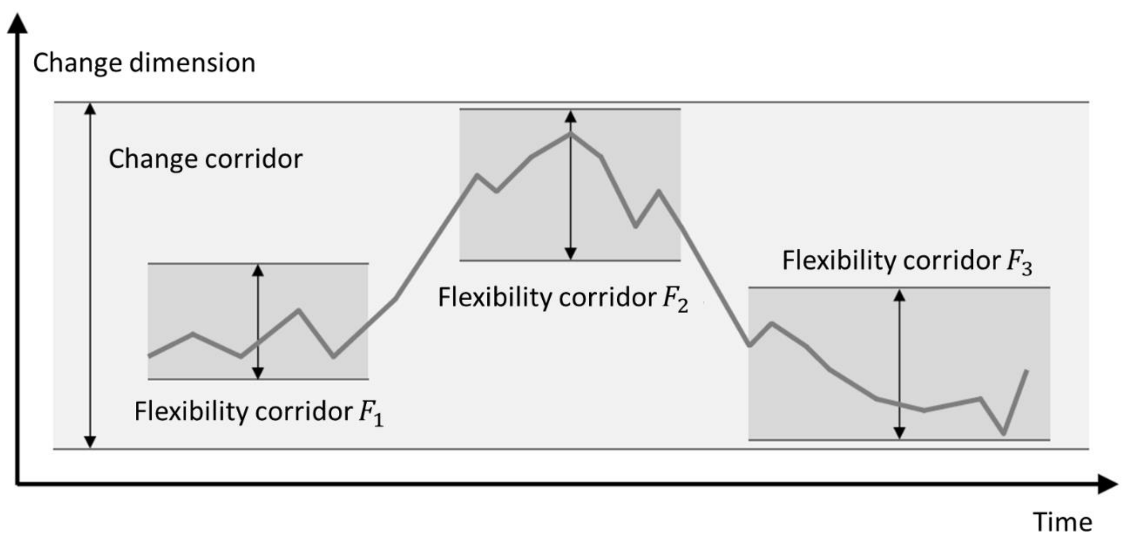


Figure 28: Difference between adaptability and flexibility corridors (Zäh et al. 2005; Fisel 2018)

Eicher (2020) formulates the relationship as follows: "A flexible system is thus only adaptable within existing limits - so-called flexibility corridors - when disturbances occur. In an adaptive system, these flexibility corridors are shifted. In this way, it is also possible to react efficiently to major changes that can no longer be handled by flexibility". (Eicher 2020) Changes in flexible systems during operation are usually limited mainly to set-up efforts, which means that system flexibility is usually associated with relatively low direct and indirect costs and time delays. Adaptability, on the other hand, refers to a longer-term decision horizon and also considers matters such as investment in machinery and equipment and the hiring of new personnel. (Fisel 2018)

Flexibility types

Different types of flexibility can be found in the literature. The types of flexibility frequently cited are process flexibility, routing flexibility, machine flexibility and volume flexibility. Different scholars have developed detailed definitions and derivation possibilities (ElMaraghy 2005; Braglia and Petroni 2000; Müller 2016, S.41ff; Eicher 2020, 44ff). *Process flexibility* is the ability of the production system to produce a given set of product types and variants without changing the set-up (Braglia and Petroni 2000; ElMaraghy 2005). *Routing flexibility* is defined as the "ability to produce a part type via multiple routes and/or perform different operations on more than one machine" (Zammori et al. 2011). Braglia, in turn, describes it as the ability of the manufacturing system to produce a part type in different alternative ways. This dimension refers to the ability to handle failures and continue production of the given set of part types (Braglia and Petroni 2000). *Machine flexibility* is described as the ability to make the necessary changes to machines to move from one set of parts to another (Braglia and Petroni 2000). Alternatively, as a definition for machine flexibility, the various operations are carried out without a change of set-up (ElMaraghy 2005). *Volume flexibility* is the ability to produce profitably and efficiently at different volumes without structural changes (Braglia and Petroni 2000). In other words, the ability to profitably vary production volume within production capacity (ElMaraghy 2005).

For the comparison of flexibility characteristics, there are different approaches in the literature for calculating flexibility types. Galizia et al. (2020) describe a platform reconfiguration index (PRI) and platform customisation index (PCI), which evaluate the reconfiguration and customisation effort of production platforms, considering the number of variants and the number of tasks. Some approaches, such as the one by Andersen et al. (2018), aid in identifying potential for improvement, but also concrete mechanisms to improve flexibility and adaptability in the company.

2.4.2 Load and stress

The assessment of human well-being in the context of an activity is not trivial. In addition, even with the same load, for example the same weight distribution or other external influences, the individual perception of the load and thus the physical and mental strain (stress) is not the same for different people. There are both intra-individual differences, for example depending on the form of the day, and inter-individual differences between individuals (Schmidt and Thews 1977). In order to clarify this important aspect, the stress-strain principle is first introduced. Stress is understood to be "The totality of all influences from the work task, work environment and work organisation that can have an effect on people" (Knauth). Many of these stress factors, such as weight, energy consumption and pollutant concentration, can be measured. Stress, on the other hand, is not directly measurable. It is only possible to ask employees about their perceptions or to relate measured values to the stress on people (Knauth).

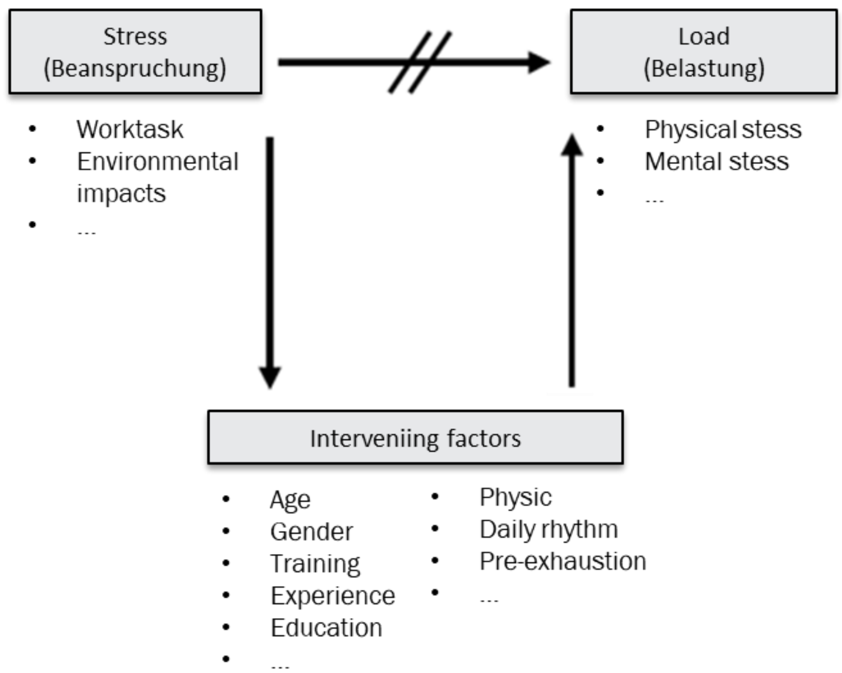


Figure 29: Load (Belastung) and stress (Beanspruchung) (Knauth)

The central factors for the stress as a reaction to a load are the degree of effectiveness, i.e. the efficiency of the work and the performance of the employee, which results from the state of health and training, as well as from environmental and psychological influences. Several types of stress can be distinguished, which in practice usually occur in combined form. Physical load includes dynamic work, in which physical work is performed along a path against resistance and the body performs isotonic and auxonic muscle contractions, and static work, in which isometric muscle contractions are performed and which is therefore also called holding work. Mental workload includes mental and emotional components. Mental strain occurs during the perception and processing of information and signals with the help of intellectual abilities. Emotional strain, which results from the mood at the workplace, is favoured, for example, by arguments, deadline pressure, noise or shift work. Stress in assembly line work, which is also referred to as sensory-motor or dexterity stress, combines both physical and mental stress components (Schmidt and Thews 1977).

Typical performance curve

In manual assembly, i.e. a process in which the human being is at the centre and uses his or her skills and energy with the aid of tools to carry out certain operations, the human being cannot produce a constant output over several hours or an entire 8-hour shift. Kaminsky's diagram, which was taken up by Lotter and Wiendahl, illustrates a standard daily course of human performance in relation to normal performance. As employees' performance varies, so does their workload (Lotter and Wiendahl 2005).

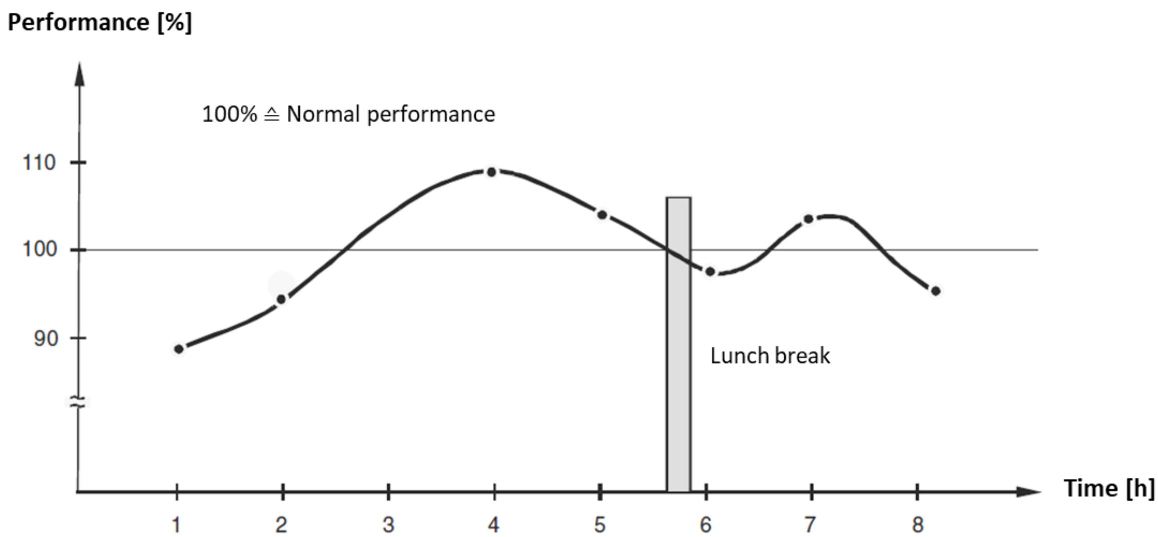


Figure 30: Typical performance curve (Kaminsky) in (Lotter and Wiendahl 2005)

Self-regulation

A concept that deals with a person's ability to cope with stress, including the emotional and mental dimension, is the concept of self-reulation presented by Muraven and Baumeister (2000). Self-regulation, is described as the ability to put a controlled effort into the task at hand. This includes physical, spiritual and mental capabilities. According to Muraven, this ability is limited. In some cases, it can be observed that after breaks physical and mental resources recovered and emotional well-being improved (Paton 2018).
Studies by Gailliot (2007) successfully demonstrated that glucose levels can serve as a measurable indicator of self-regulatory capacity. Strong efforts of self-regulation were reflected in a decreasing glucose level (Trougakos and Hideg 2009).

Continuous power limit and steady state

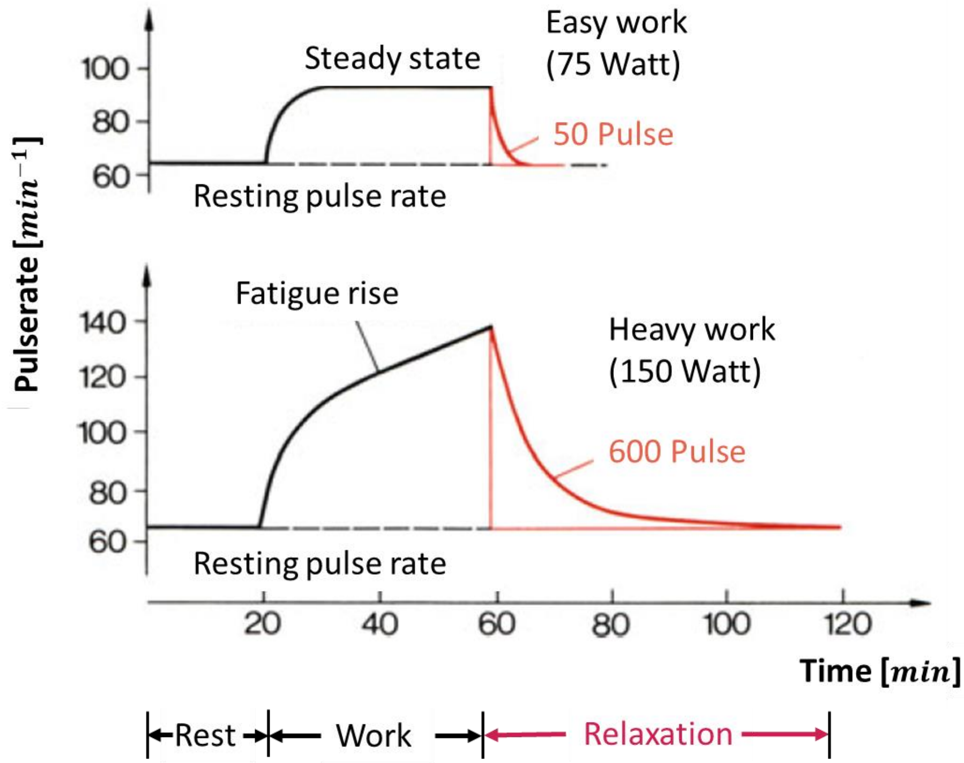


Figure 31: Heart rate and work (Schmidt and Thews 1977)

The diagram shows the behaviour of volunteers of average capacity during light and heavy work with constant power. It shows two different cases of how the power can affect a person and their pulse response. The reddish areas visualise the recovery sum. At a lighter work intensity (load ≤ continuous power limit), the pulse rate settles at a certain level and an oxygen equilibrium is reached. This state is also called steady state. The worker can perform the activity at this intensity for a longer period of time and after the end of the work, the pulse rate quickly recovers to the resting value. On the other hand, in the case of heavy work (load > continuous output limit), O_2 equilibrium cannot be achieved, which means that the pulse rate continues to increase and does not level off. Exhaustion forces a termination. After this type of exertion, it takes a relatively long time to reach the initial resting value. By compensating with breaks, short-term work above the continuous performance limit can be made possible (Knauth).
In order to illustrate how the pulse rate behaves when an employee performs above the continuous power output and the duration of an intermediate recovery break is not sufficient so that the resting value can be reached, a comparison is made with interval training in running. The following graph shows the course of the pulse rate during interval training, consisting of a sequence of short-time loads with interspersed recovery breaks (Pitsch and Pitsch 2014).

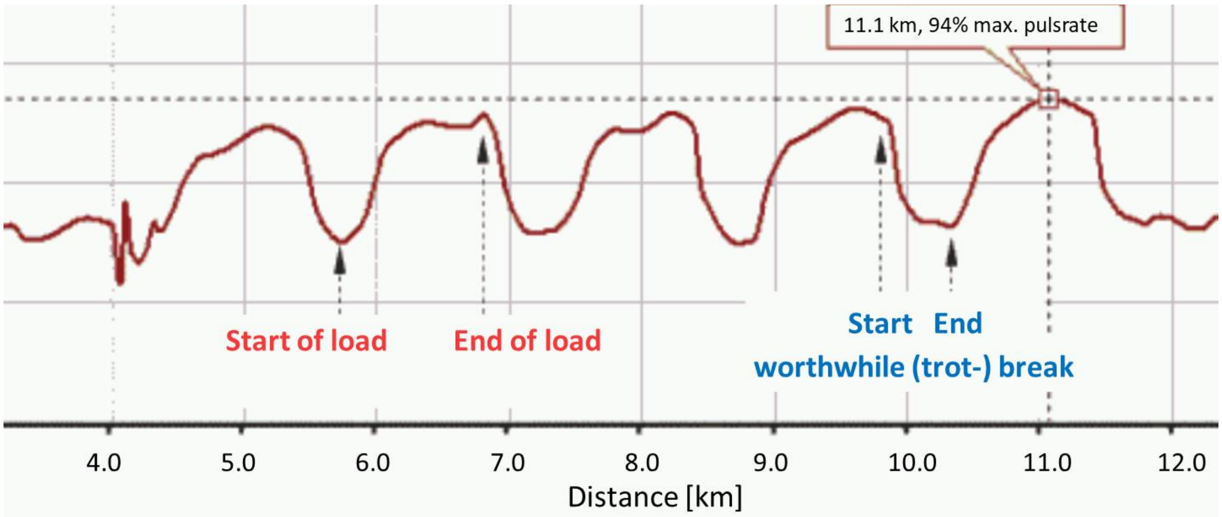


Figure 32: Pulse rate measurement during interval training (Pitsch and Pitsch 2014)

Oxygen demand and tissue metabolism

The aim of respiration is to transport oxygen to the body's cells to enable biological oxidation of nutrients, which releases energy. Carbon dioxide (CO_2) is released as a metabolic product. Both O_2 and CO_2 are transported by capillary blood. Cell energy production can occur in an aerobic or anaerobic manner. Under normal conditions, the body cell obtains its required amount of energy through oxidative degradation, also known as aerobic utilisation of nutrients. If both nutrients, also called substrate (protein, fat, carbohydrate), and oxygen are available, then the aerobic process is prioritised by the body cells. In this case, glycose is used for energy production so that the body cells can maintain their structure and perform their function even when the oxygen concentration is insufficient. In this alternative, the body cell does not need oxygen, but the energy content of the lactate (lactic acid) produced is still significantly higher than that of CO_2. For this reason, the body requires about 15 times more energy in anaerobic mode than in aerobic mode. In addition to the increased glycose requirement, the removal of the lactate formed also presents the tissues with a challenge, which means that the anaerobic mode is not permanently possible. Between rest and hard work, the oxygen demand of the organs can vary greatly. For example, the oxygen consumption $\dot{V}_{O_2}$ for the bones varies between 0.25 - 0.5 to approx. 10 ml/100 g-min O_2 and for the heart from 10 to approx. 40 ml/100 g-min O_2. Since the O_2 demand increases with an increased strain on the body, the O_2 supply must also increase. The cells are supplied by diffusion of arterial oxygen. This can only be achieved by increasing the oxygen concentration in the blood or by increasing the blood volume. Since the O_2 saturation of the haemoglobin in the arterial blood is already approx. 97% in the normal state, the oxygen supply to the cells is primarily adjusted by adjusting the blood flow (Schmidt and Thews 1977). Therefore, the pulse rate can be interpreted as a direct indicator of individual stress, through which the body's cells require more energy.

Oxygen intake

In general, it can be said that oxygen uptake is proportional to the workload. If a steady state is reached during light work, this means that there is a balance between the intake and demand for oxygen. The adjustment of the equilibrium state takes about 3-5 minutes at the start of exertion due to the adaptation of the metabolism and the blood circulation. During this time, the body draws on the oxygen store myoglobin-O_2, which, however, can only supply small amounts of oxygen. The inertia of aerobic muscle metabolism therefore leads to an initial oxygen deficit. With heavy work, unlike with light work, no oxygen equilibrium is reached, but the uptake of oxygen continues to rise in a similar way to the pulse rate. The oxygen deficit therefore also increases. After the end of exertion, an oxygen demand above the resting value continues to be observed for some time during heavy and light work. This pays off the accumulated oxygen debt. The following diagram shows the oxygen demand during dynamic work (Schmidt and Thews 1977).

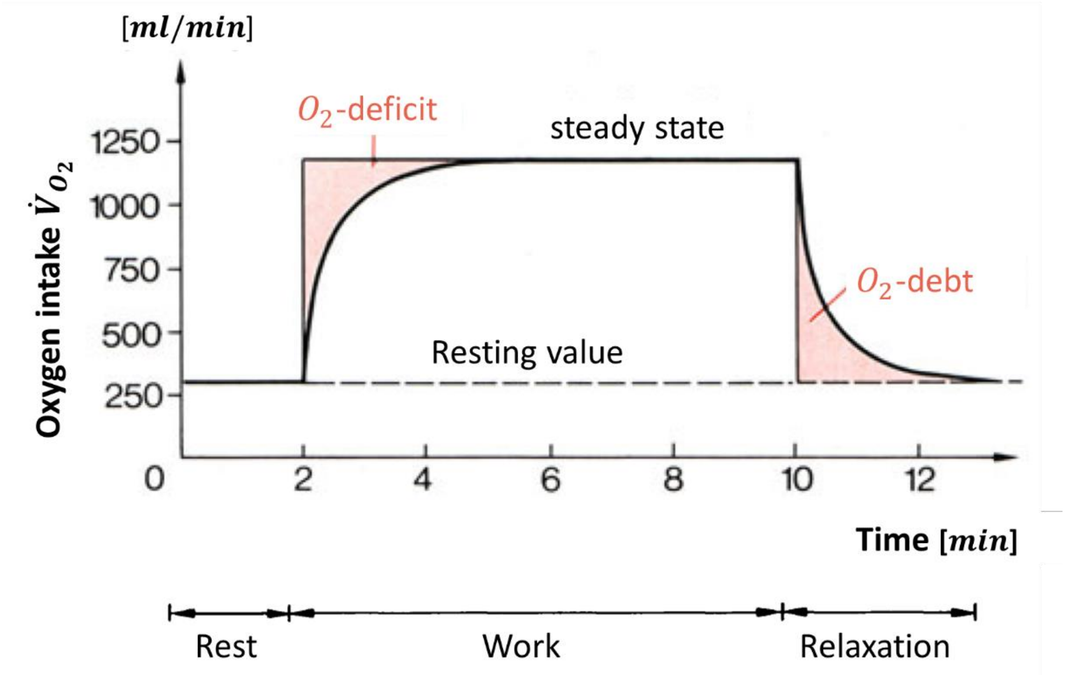


Figure 33: Oxygen uptake and oxygen debt

Under stress with constant or varying degree of performance, the oxygen uptake is proportional to the pulse rate. At constant efficiency, this also applies to the relationship to power. As a tendency, it can be said that with increasing pulse rate, a smaller increase in oxygen uptake is associated with children and adolescents than with adults (Schmidt and Thews 1977).

Oxygen saturation

The oxygen saturation in the blood indicates to what extent the haemoglobin of the blood is saturated with oxygen. Oxygen saturation is expressed as a percentage with the SPO_2-value and measured with so-called pulse oximeter sensors.

Different factors can cause a reduction in the oxygen binding capacity of haemoglobin and thus in oxygen saturation. For example, increasing stress leads to tissue acidosis, i.e. an acidification of the blood. In addition, body temperature and CO_2-partial pressure increases due to oxygen debt. There is also an increase in 2,3-bisphosphoglycerate (2,3-BPG), which regulates oxygen binding to haemoglobin. This makes it easier for oxygen to diffuse (be released) into the tissues, but the haemoglobin binds oxygen less strongly, which means that the oxygen saturation in the blood decreases and the breathing rate must increase. The described relationship is also called the Bohr effect and suggests that oxygen saturation can serve as an indicator of stress.

Body reactions to non-physical stress

External factors can stress people not only physically, but also mentally and emotionally. Due to increased muscle tension and not due to an increased energy demand of the brain, the energy metabolism of the body also increases due to mental stress. For this reason, physical reactions can also be observed during mental stress, similar to physical stress. The following reactions are worth mentioning: Increase in pulse rate, respiratory volume, blood flow, decrease in electrical resistance of the skin, increased sweating and adrenaline release into the blood, which can be detected in the form of vanillin-mandelic acid in the urine.

Conclusions about the individual stress of physical reactions to psychological (also combined with physical) stress are possible but much less reliable than for physical stress. Other indicators of psychological and emotional stress, such as those that occur during anxiety or excitement, can be heart palpitations, hyperventilation and sweating. In life-threatening situations, this can lead to spontaneous incontinence or cardiac arrest (Schmidt and Thews 1977).

Skin temperature and skin conductivity

Papaestfanou (2013) was able to show how skin conductivity and skin temperature (measured on the forehead or fingers) behave in a study in which test persons were shown amputation videos or asked to quickly inflate a balloon. With his experiments, he was able to confirm findings from the research literature (Kreibig 2010; Rimm-Kaufman and Kagan 1996; Boudewyns 1976) that skin conductance values increase and skin temperature values decrease in threatening situations or stressful episodes (Papaestefanou 2013). Short-term reactions can therefore be used to identify acute stress reactions, which can enable an assignment to a specific event.

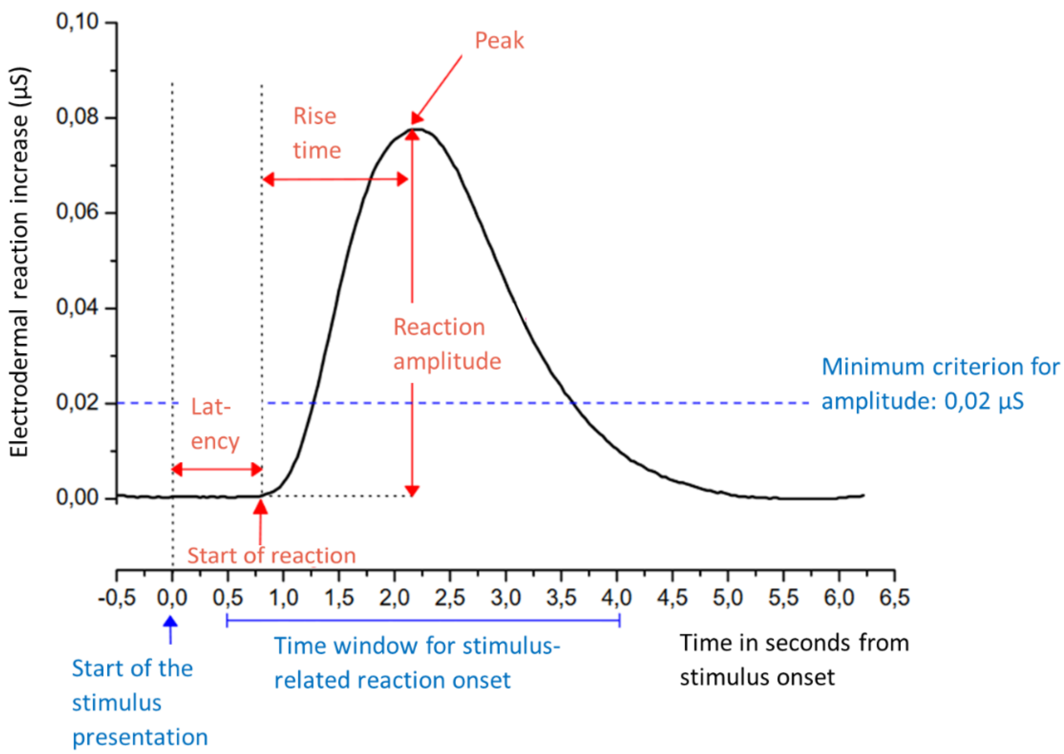


Figure 34: Exemplary electrodermal reaction with its important determinants latency, rise time and reaction amplitude (Burk 2005)(Mertens 2016)

Communication analysis as an indicator of stress

In his dissertation, Schuller (2006) describes approaches for assessing emotional stress with the help of a machine analysis of linguistic and manual interpersonal interactions (Schuller 2006).

Possibilities for the classification of load and stress

The REFA classification distinguishes between light work, light to medium work, medium work and heavy work. This scale is used, for example, in the Social Medical Glossary of the German Pension Insurance. Decisive for the categorisation are the forms of movement, posture, weight and duration of the activity.

However, this only describes the strain of the activity and not the individual stress of the employee (Sozialmedizinisches Glossar, p. 22).

In order to avoid self-report bias problems in stress assessment (Papaestefanou 2013), various body responses were considered that offer potentials for emotion-free and unbiased real-time measurement in the assessment of employee stress. Even though this goal is desirable, the survey of employees is still the most meaningful indication of strain. Therefore, in the following, possibilities of recording the perception of effort in employee surveys are shown.

One way of recording the feeling of exertion is to use psychometric estimation scales such as the Borg scale, in which the test persons indicate their exertion on a number scale. Scales from 6 to 20 are common in athletics. However, there are also adapted variants such as the Borg scale modified by (Boutellier and Ulmer 2007). The following applies to the rating of perceived exertion: 0 = none/none; 0.5 = very, very small (just noticeable); 1 = very small; 2 = small, 3 = moderate; 4 = moderately large; 5 = large, 7 = very large; 9 = very, very large (almost maximum); 10 = maximum (Boutellier and Ulmer 2007).

There are other scales in the literature for measuring the intrinsic condition. Nitsch (1976) has assessed stress criteria on a scale of 1-6, with 1 = hardly, 2 = somewhat, 3 = to some extent, 4 = fairly, 5 = predominantly, 6 = completely (Schlick et al. 2010).

2.4.3 Competence

Competences include qualifications, skills and knowledge, but cover more areas than these and also include individual values and norms that influence behaviour in a variety of situations.

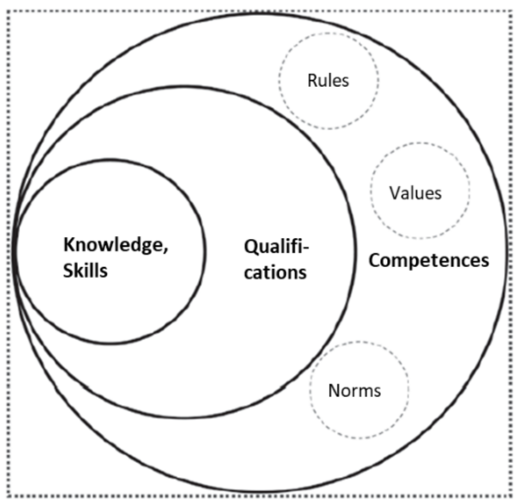


Figure 35: Competences, qualification and skills & knowledge (Faix 2012)

In reality, there are countless key competences and recording all types of competences is a challenge. With the KodeX Atlas comprehensive overview of different types of competences is provided, which categorises them into 4 basic competences: Personal (P), Activity-related (A), Functional-methodical (F) and Social-communicative (S) competences (Faix 2012).
Personal competences (P) refer to self-organised and self-reflective action and productive, creativity-promoting attitudes and values.

Self-organisation and willpower in achieving results involving values and knowledge are summarised as *activity-related competences* (A)

Functional and methodological competences (F) refer to the ability to be methodologically and professionally equipped to solve difficult problems and to cope with them creatively.

Social-communicative competences (S) are necessary to be able to cope with interpersonal and inter-organisational situations and challenges of all kinds (conflicts, maintaining contacts, etc.)

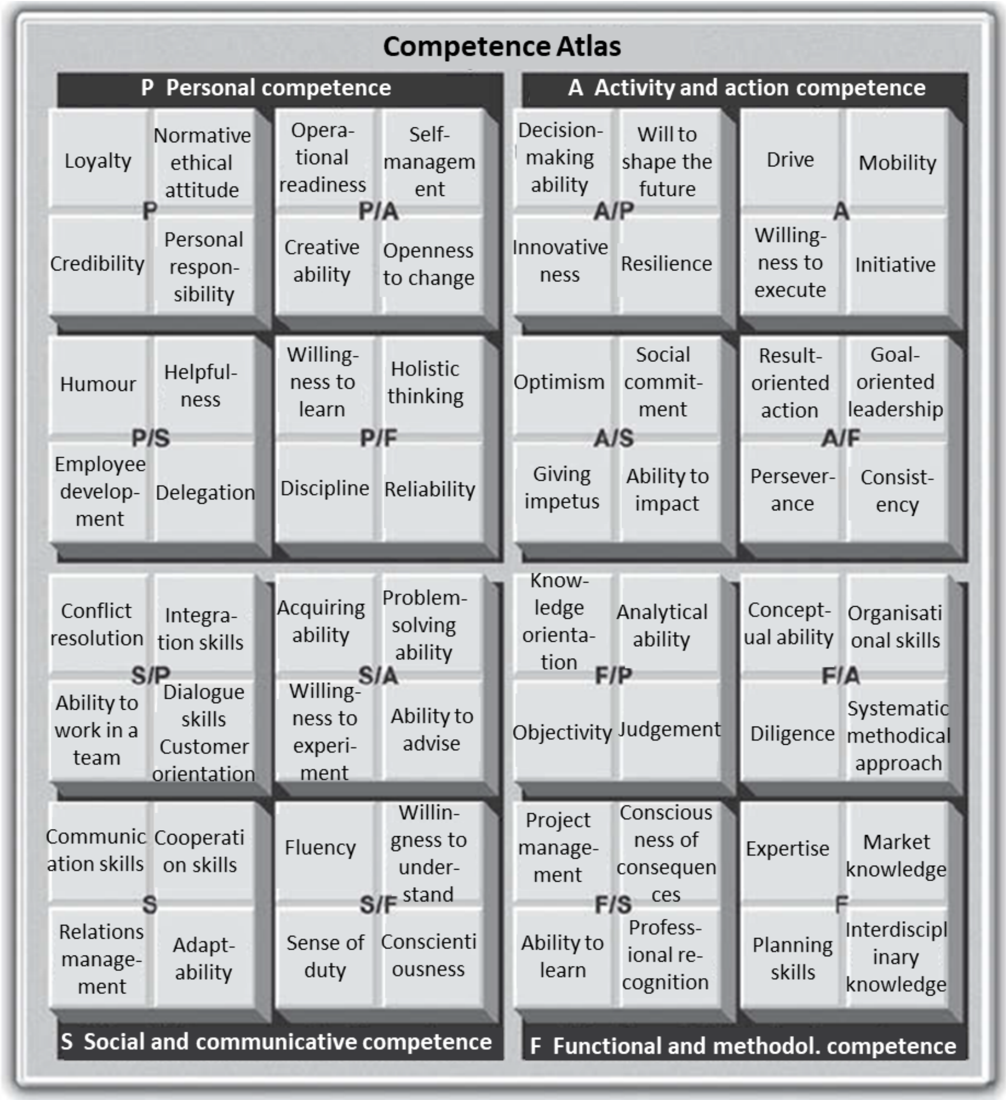


Figure 36: KodeX - Competence Atlas (Faix 2012, p. 44)

He also describes a procedure with which a comparison can be made between a target profile and the assessment of employee competence for selected types of competence. Faix recommends using the following procedure to derive a case-specific assessment system based on the KodeX Atlas. The procedure is as follows. First, competence types that are considered relevant for the specific consideration of the individual case study are selected. This is followed by a company-specific definition of the competence types in the context of the use case. In the third step, a job group-specific profiling is carried out, which provides employee profiles as a result. Finally, the development of a corresponding rating procedure is recommended. The aim is to create a rating system according to individual preferences.

The following figure shows an example (Poffenberger KodeX) which is based on the KodeX Atlas. It contains 16 selected types of competences, which are rated on an ordinal scale from 1 (less pronounced) to 12 (excessively pronounced). The rating success is achieved by colleagues, supervisors and by the person being rated. A target profile representing the requirements for each competence type is also presented.

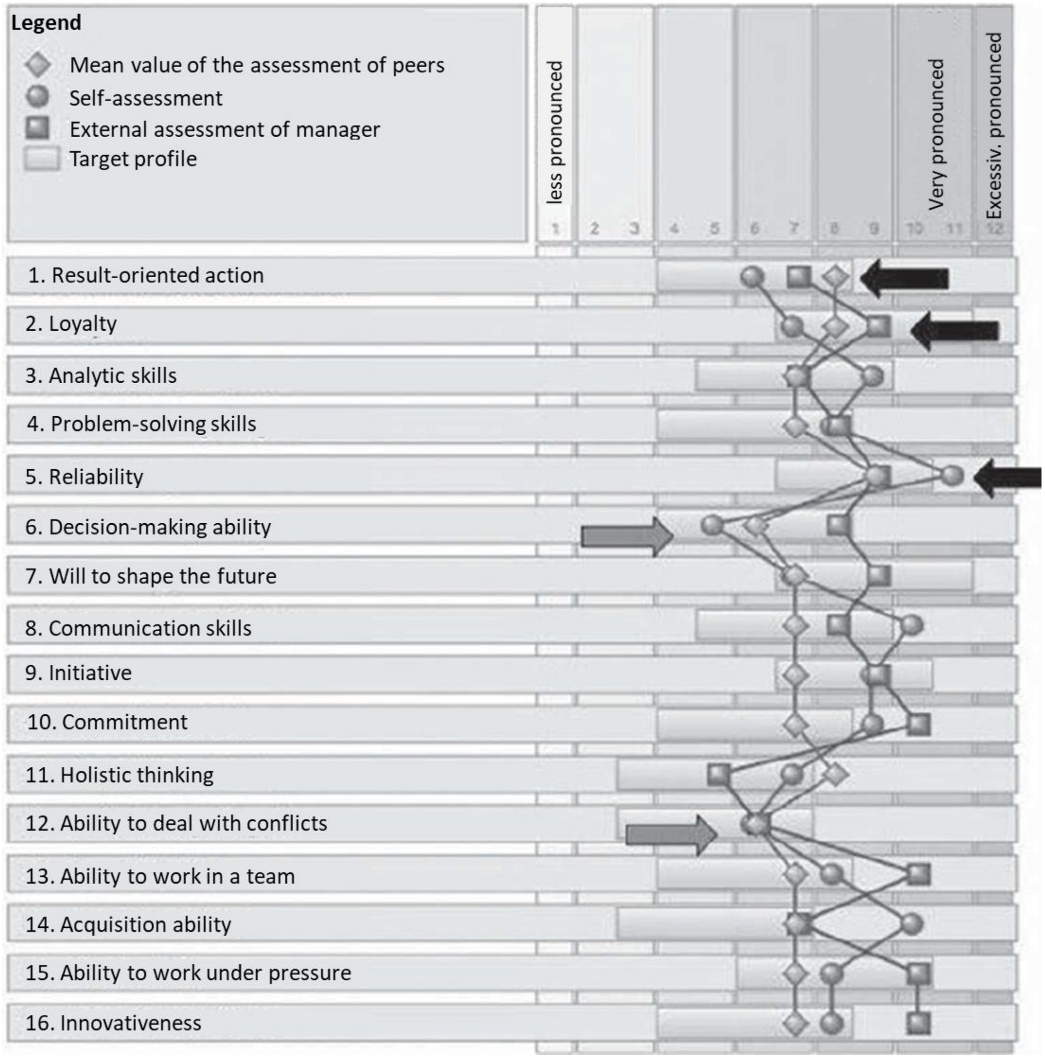


Figure 37: Example of a competence assessment (with 8 third-party assessments, 1 self-assessment and assessment by a company representative) (Faix 2012, p. 103)

In the presentation of the concept, it is clearly emphasised that the KodeX Atlas can serve as a basis for a wide variety of assessment forms and that an individualisation or tailoring of the concept and the assessment procedure to the specific application is not only permitted but recommended.

Ecology

The term ecology generally encompasses the environmental compatibility or harmlessness of nature and the environment. This refers, for example, to the protection of nature, the renewability of raw materials and the avoidance of pollutants and emissions. A frequently addressed aspect is the emission of the greenhouse gas carbon dioxide (CO_2).

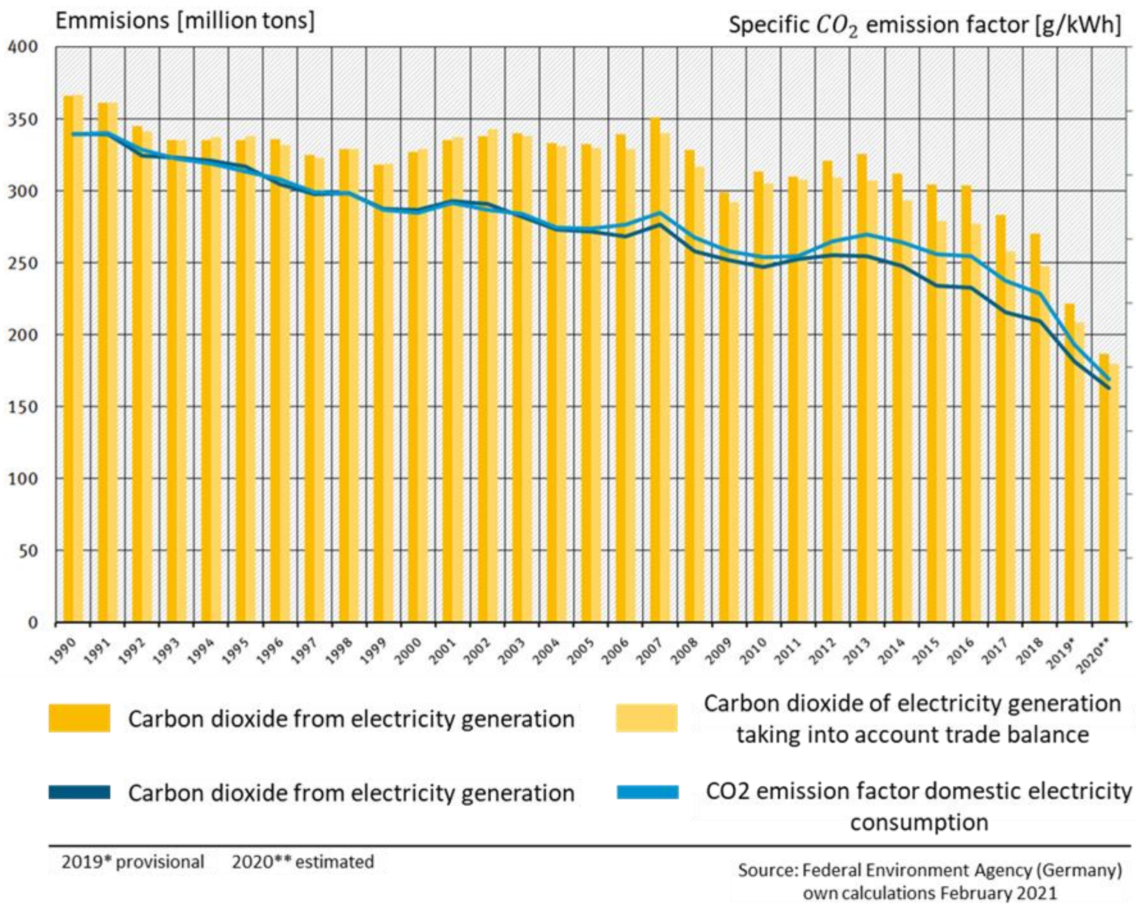


Figure 38: Development of specific carbon dioxide emissions of the German electricity mix 1990-2019 and first estimates 2020 compared to C02 emissions of electricity generation (Federal Environment Agency)

The electricity mix (Germany) shown is a measure that forms an average value based on total electricity consumption and total CO_2 emissions per year in Germany. In 2020, it is estimated that 0.4 kg of CO_2 will be emitted on average per kWh of energy.

2.5 Digital twin and simulation

2.5.1 Simulation methods and concepts

According to VDI3633, simulations of dynamic systems can be divided into continuous and discrete methods. Continuous simulations involve steady state changes, which makes sense for physical-technical applications but is less relevant in logistics and planning. In discrete simulations, a finite number of (discrete) changes of state are represented in a period of time. The time progress can be event-oriented or discrete in time. In discrete-event or event-oriented simulations, events are considered at given points in time and decide on the state adjustments. In activity-oriented simulation, the activities that can be triggered are investigated in time sequences. In process-oriented simulation, parallel interacting processes are mapped. A special form of this is the transaction-oriented simulation, which enables a differentiation between transactions (mobile dynamic objects) and stations (permanent static objects) (Venn 2010).

In the literature, some concepts can be found that have elements that are also used in the simulation-based system for configuring the assessment of CPPS developed in this research work. In his paper

"Adaptive Production Control in a Modular Assembly System Based on Partial Look-ahead Scheduling", (Mayer and Endisch 2019 - 2019) describe an approach to design CPPS in a modular and dynamic way. For this purpose, they also use a simulation as well as a computational model to compare different scenarios. The focus is mainly on optimal order scheduling. Qualitative evaluation aspects are left out of the evaluation.

In his dissertation on "Automatic simulation-supported work planning in assembly", (Michniewicz 2019) presents on the one hand a design approach in which assembly is divided into sub-steps, which are then assigned to the actors/stations (humans, robots, transport systems, ...), and on the other hand a simulation of the alternative assembly processes and the economic evaluation of the scenarios. However, only easily quantifiable aspects are considered in the evaluation of the scenarios. An extension of the economic calculation, as it is made possible for example with the help of the work system value, is not considered (Michniewicz 2019).

2.5.2 Digital model, shadow, twin

The following diagram shows a definition that distinguishes between the digital model, the digital shadow and the digital twin depending on the automation of the information flow. With the digital twin, there is a two-way automatic data flow between the digital and physical object.

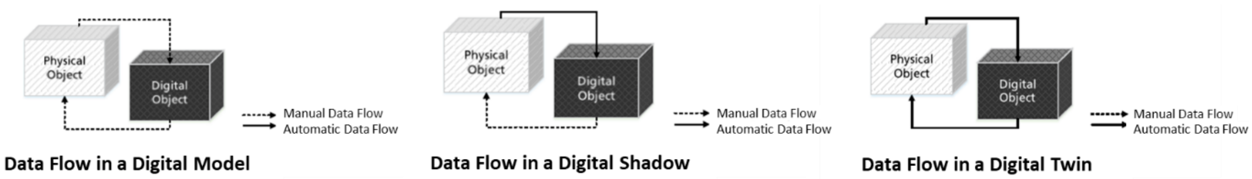


Figure 39: Digital Model, Shadow, Twin (Kritzinger et al. 2018)

Digital twin technology was initially applied in NASA's Apollo project and defined as an "integrated multi-physics, multi-scale simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, ect., to mirror the life of its corresponding flying twin (Glaessgen and Stargel 2012). In the context of cyber-physical systems (CPS) and CPPS, this can refer either to the transfer of the product into a virtual form that spans the product lifecycle. Alternatively, in the production environment, the digital twin can be tailored to design shop floor activities, production lines and process flows, helping to bridge the gap between the physical and digital production systems. (Ding et al. 2019)
In his publication, (Monek et al.) describe in a very clear way the functioning of a (steady-state) digital twin-based simulation framework for predictions. This model is specially developed for event-discrete simulations.

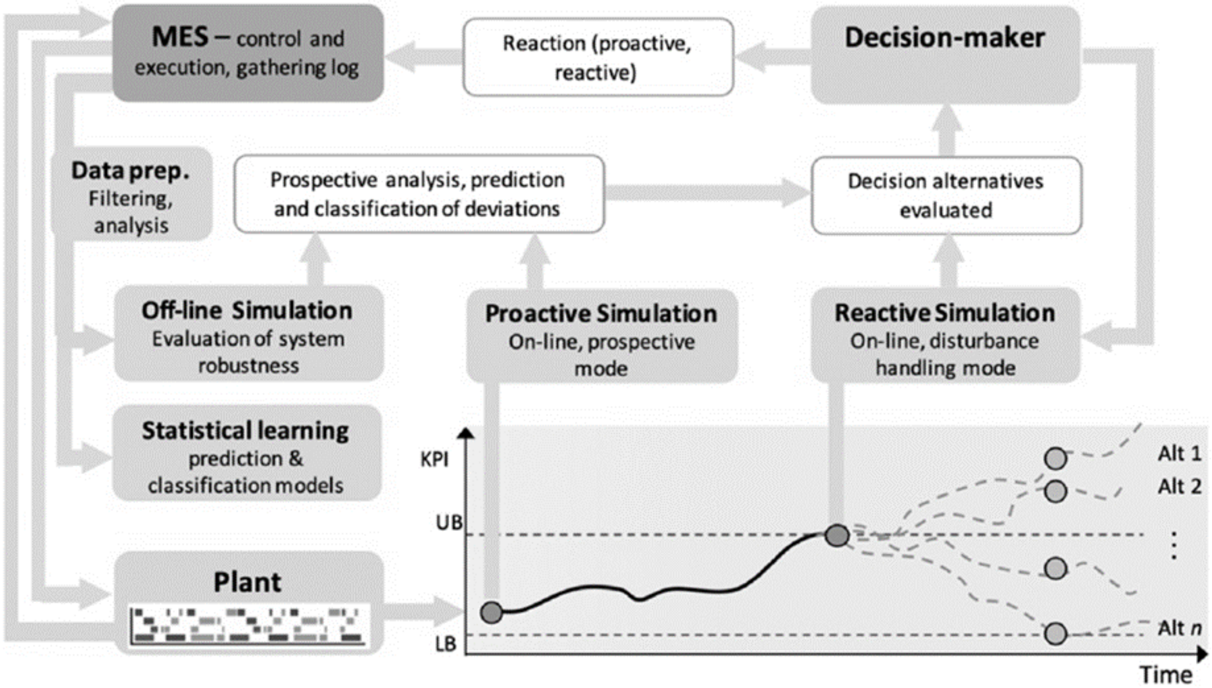


Figure 40: Proactive planning and prescriptive simulation (Monek et al.)

(Zhang et al. 2019) deal with Digital Twin based smart shop floor in CPPS and proposes with the following diagram a new architecture for CPPS consisting of the 5 layers: Physical layer, network layer, database layer, model layer and application layer.

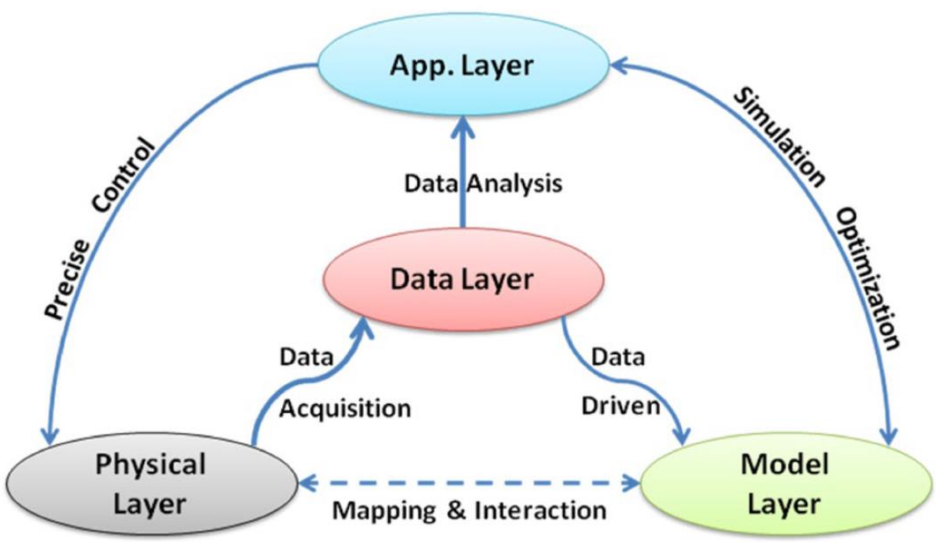


Figure 41: Scheme of digital twin-driven CPPS [Zhang 2018]

For this purpose, a procedure for job scheduling based on digital twin-driven CPPS is presented with a case study. The method follows a 5-step process. Step1: Data collection; Step2: Creating interaction between physical and model layers; Step3: Applying intelligent algorithms (mathematical formulas) and providing results; Step4: Further data collection in case of errors and update of model layer; Step5: Re-application of algorithms and communication to planners, etc. (Zhang et al. 2019).

2.5.3 Literature summary and conclusion

The literature review helped to provide an overview of economic efficiency procedures and extension approaches. Principles and frameworks have become clear, which help to create an assessment concept for the developed systematics of this research work. The variety of possible effects that can be included in an evaluation, the challenge of quantification and the interdisciplinary nature of the influencing factors have made the complexity of the topic clear. For different elements of the systematics to be developed, such as the design of system configurations, extended evaluation logics, operationalisation approaches for criteria that are difficult to quantify and for the design of a digital twin as a virtual representation of the production, many elaborations can be found. It became clear that there is a scientific gap for the automatic simulation and evaluation of scenarios for production scenarios, which provides the decision-maker with a processed interdisciplinary information base for holistic decision-making for production planning. And an approach that enables a sustainable improvement of the forecasting capability through continuous data acquisition.

Chapter 3
Tentative Design (Concept)

In this section, the concept of the configuration and assessment systematic is introduced. For this purpose, the model of the systematic and the intended functioning of the systematic are discussed. In addition to an overview of the system model, the sub-areas of the configuration of scenarios and the extended economic efficiency calculation are presented. The calculation logic of the individual criteria is also discussed in detail.

3.1 System model

The rating systematic contains several interrelated elements. The logic and the flow of information will now be described in a model in order to present the functionality of the system and to gain an overview of the connection of the different subsystems. Since the overall model contains many sub-elements, these will be presented separately in detail.

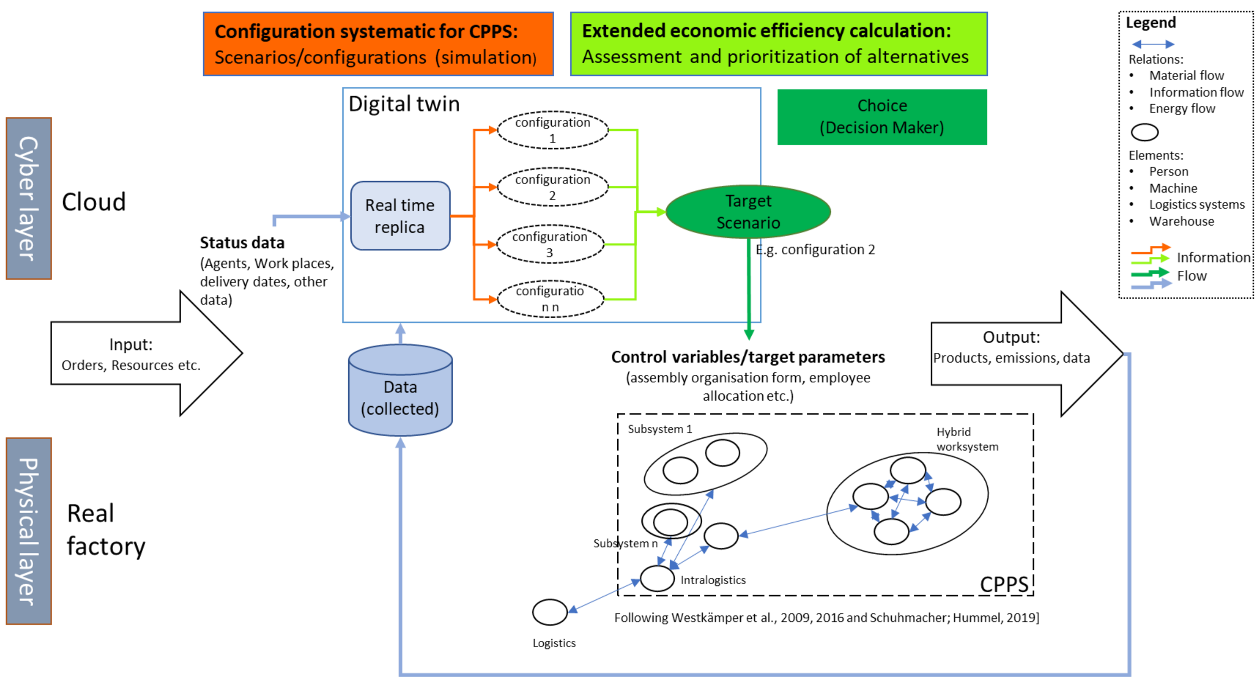


Figure 42: Simplified model of the rating systematic

The diagram above represents a simplified model of the assessment system. First, the digital twin of production is provided with the current input information regarding orders and resource availability. Based on this daily updated image of the framework conditions for production, a configuration logic can generate different scenarios consisting of different combinations of production setup, which can be varied with the choice of assembly organisation, and different employee assignments, which can be combined based on the qualification and availability of employees and agents. The system configurations made possible by these degrees of freedom are automatically assessed, based on information from the occupancy planning and simulation, with the help of an extended economic efficiency calculation. As a basis of information for the evaluation, collected data from past scenarios that have been implemented in reality are also included in order to be able to close the information gaps for the calculation of criteria such as staff utilisation. Optionally, the decision for a scenario can be made with the help of a pre-selected weighting of the work system value criteria and the costs, or it can be made by a decision maker, who can form his own transparent picture of the different evaluation aspects and their performance. Once a decision has been made, the chosen scenario can be implemented in the real factory. For this purpose, the control variables of the set-up and the staff allocation are selected according to the simulated scenario. Since a certain deviation between simulation and actual production is always to be expected, the relevant data is continuously recorded in the factory and thus expands the database of the simulation and calculation of the extended economic efficiency. In the following illustration, this information feedback, which enables continuous learning and thus an improvement of the prediction, is visualised as a model.

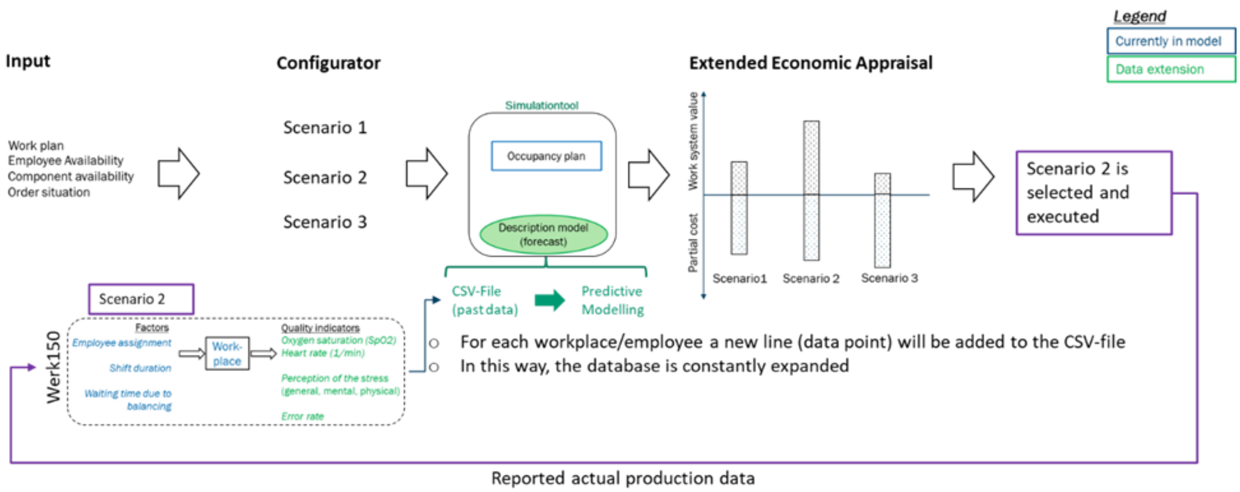


Figure 43: Learning Approach for continuous improvement of the description model

3.2 Scenario configuration

Now the degrees of freedom and possibilities for configuring feasible production assignments are presented. For each product type, depending on the availability of employees and infrastructure components such as workstations and tools, a choice can be made between individual workstation assembly or clocked line production. A further variability of the production alternatives results from the employee allocation. The qualification matrix, which shows whether an employee can perform a workplace, limits the possibilities for allocating employees. An assessment of competence compatibility, i.e. an analysis of the match between skills and preferences with job requirements that goes beyond basic qualifications, is not initially assessed in the creation of feasible scenarios, but is included in the work system value criterion competence fit.

As an example, the FlexBlue scooter product type, which is produced in the Werk150, shows how the necessary work operations can be derived from the structure of the product. When assembling the FlexBlue, the previously picked components are used to assemble the steering stem, which consists of the handlebar unit and handlebar head unit, and the base frame, which consists of the footboard unit and rear wheel unit. Once the steering stem and base frame are assembled, the two groups of components are joined together.

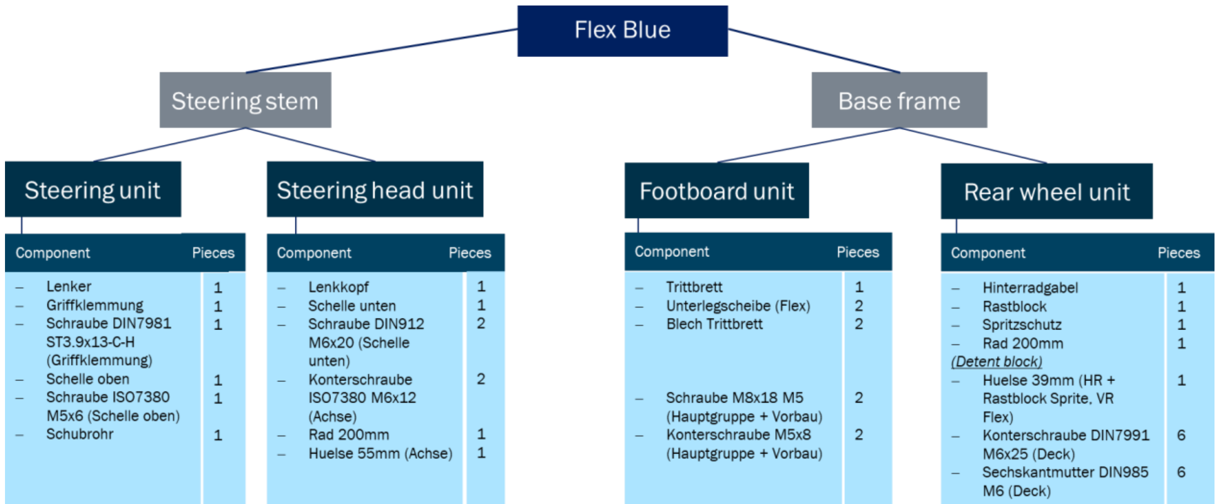


Figure 44: Structure of the product components of the FlexBlue product type

Depending on the form of assembly organisation, the work operations can either be produced in a line, i.e. distributed over several successive or parallel workplaces and workers, or they can be produced at a single workstation, where one worker performs all the work at one workplace. Of the forms of assembly organisation presented in the previous chapter, individual workstation production, clocked line production and, if necessary, semi-autonomous group production at an assembly island are suitable for the small series production of scooters. Since the exact workloads of the individual employees and the group dynamics and autonomy are very difficult to comprehend and the effort for corresponding experiments would go beyond the scope of this work, it was decided to exclude the assembly island - semi-autonomous group production from the modelling of the production alternatives for now. Therefore, each product type is assembled either at an individual workstation or in a clocked line assembly. The next diagram shows in a simplified way the allocation of the agents to the tasks, which leads to a type division as in scenario 1 or a quantity division in scenario 2.

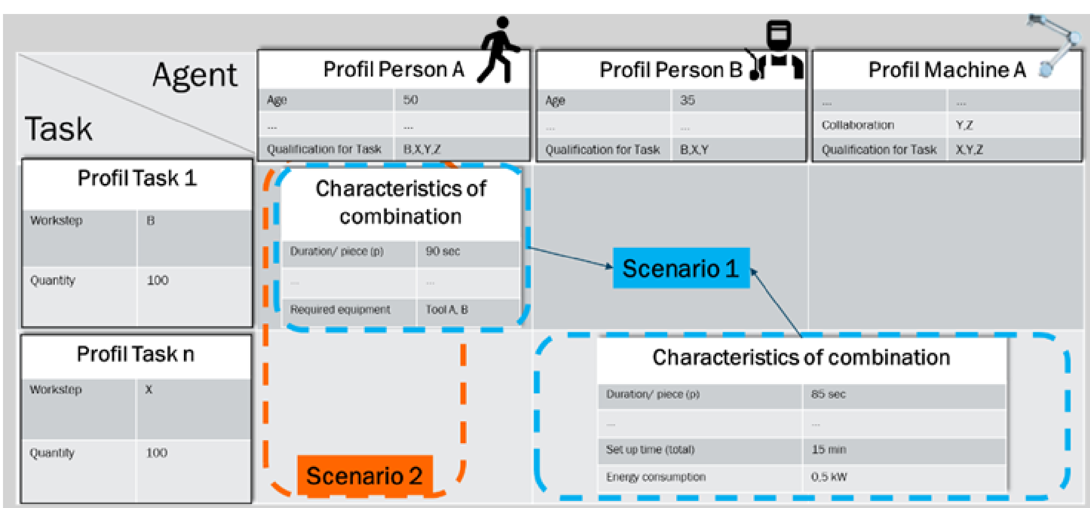


Figure 45: Scenario configuration by assigning agents and components to subtasks

3.2.1 Basis scenarios in the Werk150

The basic scenarios describe different structural forms for the respective product types and thus embody the various forms of assembly organisation. In this research work, a basic scenario for individual workstation assembly and a basic scenario for line assembly are available for configuration. An allocation of employees and current information on orders and resource availability enable the formation of the concrete scenarios.

Characteristics of small-batch scooter production at the plant150

(Hasenclever et al. 2011) present different characteristics to describe production systems. The characteristics are now described for the small batch scooter production "for experimental purposes" in the Werk150 in order to be able to understand the context of the systematics development. For the implementation of the design artefact, the two scooter types FlexBlue and BeewatecSilver are considered, each without variants. Depending on orders, the production is manufactured according to the assemble-to-order principle. The type of production can vary between one-off production and small batch production, depending on the order situation. The structure of the manufactured products tends to be a multi-part simple product for the FlexBlue and a multi-part complex product for the Beewatec Silver. Both manual and mechanised processes are carried out with the help of cordless screwdrivers, other tools and by hand. The localisation results from the binding of the work steps to the workplaces, which can only be changed by a set-up process. During assembly, each employee is assigned to a fixed workplace. (Hasenclever et al. 2011, p. 209; Müller 2016)

Product Types: FlexBlue and BeewatecSilver

In the Werk150 where most of the assembly experiments for data collection take place, two different product types are manufactured. Both products are city scooters. The first product type, the FlexBlue (FB) scooter, is an industrial product that requires assembly of finished parts.

Figure 46: Produkttyp FlexBlue (FB)

The BeewatecSilver (BS) roller, on the other hand, was developed by students at Reutlingen University and uses metal tubes and modular plug-in components from the company of the same name from the Reutlingen region, which specialises in the production of plug-in systems for industrial shelving and workstations. For the development of the rating systematic, the assembly of these two types of scooters at Werk150 was taken as the starting point.

Figure 47: Produkttyp Beewatec Silver (BS)

The production of the scooters in the Werk150 consists of work activities that serve the provision of materials, manufacturing or assembly. The overall production process of the FlexBlue scooter is completely defined in the form of a work plan and has already been verified. In this research work, the focus is exclusively on the assembly steps. For this reason, some steps are bundled into task packages for individual employees at the respective assembly workplaces.

Precedence graphs and activity sequencing

Based on the verified work plans of the rollers, simplified basic scenarios for the assembly experiments were designed. The following diagram shows the workplaces and their precedence relationship for the two product types, both for line assembly and for the individual workplace. Subsequently, the activity diagrams of the basic scenarios with times from the verified work plans for line assembly and the expected values calculated on the basis of (Lotter and Wiendahl 2005, p. 135) for the individual workplaces are also shown.

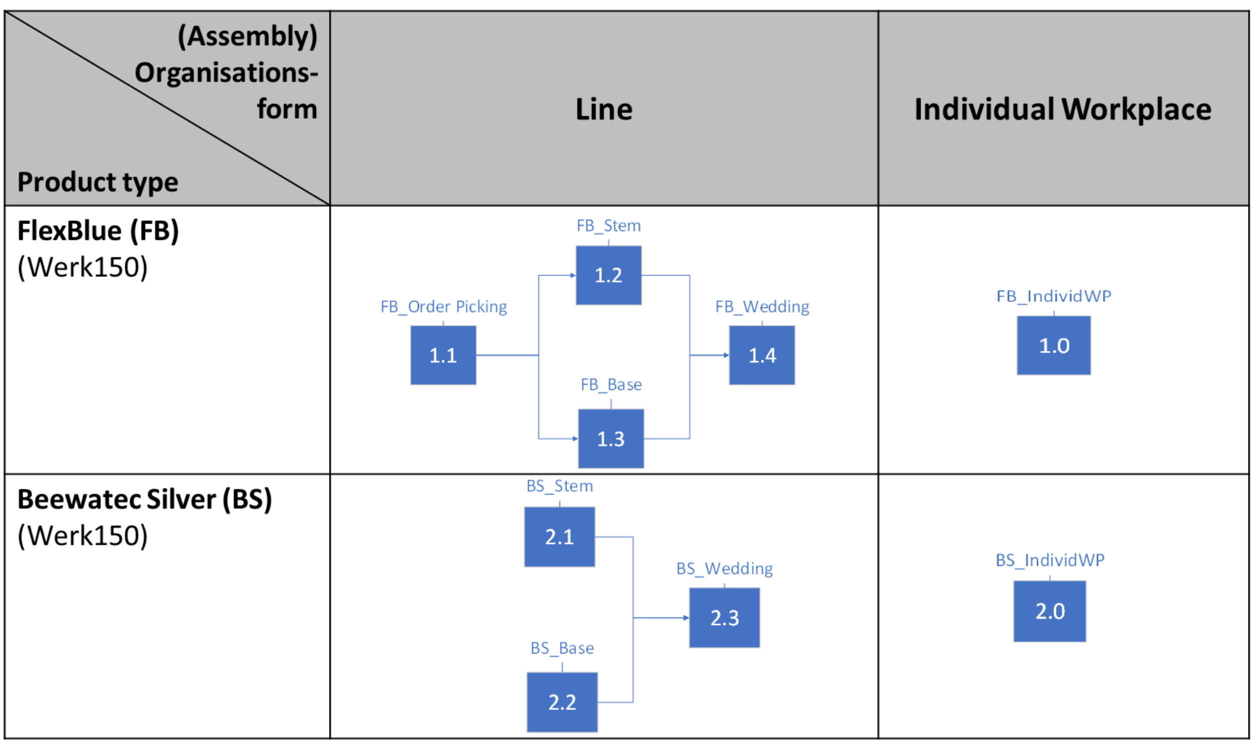


Figure 48: Precedence graph of the workplaces of the base scenarios

For the model, the work schedules were simplified in that the scopes that are completed at a workplace are summarised and thus a machine group with known hourly costs and electricity consumption (for active use and the creeping current) can be stored for each workplace. Likewise, exactly one employee is assigned to each workstation. In the case of individual workstations, all tools must be available at the workplace and the employee must have mastered all work steps for the entire assembly process. A special feature of the individual workstations is that there are no waiting times due to clocking out. There is a total of four basic scenarios for the two roller types. In addition to the line assembly of the FlexBlue roller and the line assembly of the BeewatecSilver roller, the individual workstation assembly of the FlexBlue roller and the individual workstation assembly of the BeewatecSilver form further basic scenarios.
For the basic scenario of individual workplace installation of the FlexBlue, the corresponding activity sequencing is shown below.

Nr.	Activities FB_Individual WP	
1.0	FB_individual WP	Order picking
		Assembly stem
		Assembly base
		Wedding, Quality control and packing

1.0		
0	21,78	21,78
0		21,78

Activity name/ number		
ES	D	EF
LS		LF

ES: Early Start
LS: Late Start
EF: Early Finish
LF: Late Finish
D: Duration

Figure 49: Activity sequencing for the basic scenario FB _Individual WP assembly

The line assembly of the FlexBlue scooter is distributed over 4 workstations. The first workstation is used for picking the scooter parts and is the precursor for the two workstations of stem assembly and base assembly. In the fourth and last step, the so-called marriage, the two previously produced parts, steering bar and footboard, are joined together. For reasons of improved synchronisation, the tasks of quality inspection and packaging are also carried out at this workstation. Logically, the wedding can only start when both the Stem and the Base have been assembled. During the assembly experiments, the dismantling of the scooters was also carried out to ensure that enough material is available to be able to assemble for the entire duration of the experiments.

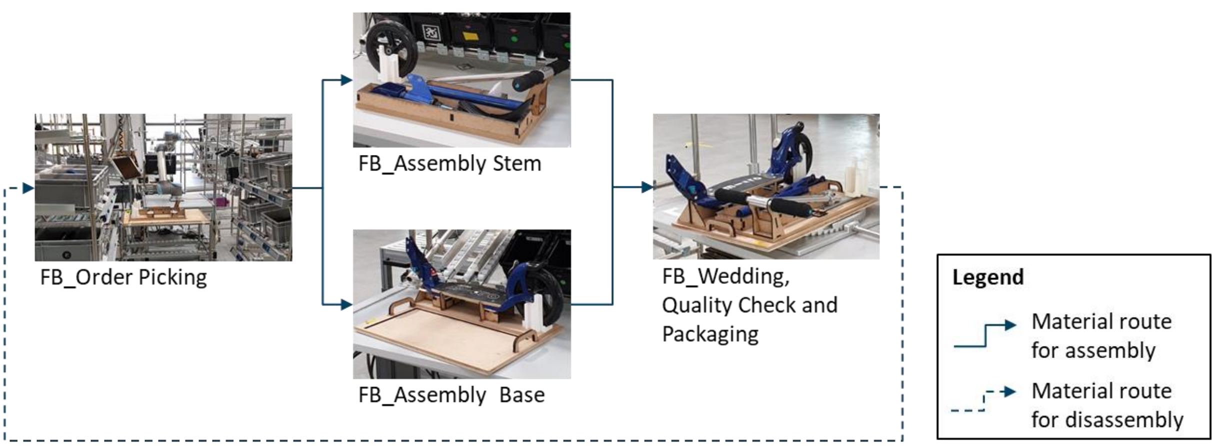


Figure 50: Basic Scenario FB_Line Assembly

The following shows the associated activity sequencing of the line assembly of the FlexBlue.

Nr.	Activities FB_Line
1.1	FB_Order picking
1.2	FB_Assembly stem
1.3	FB_Assembly base
2.1	FB_Wedding, Quality control and packing

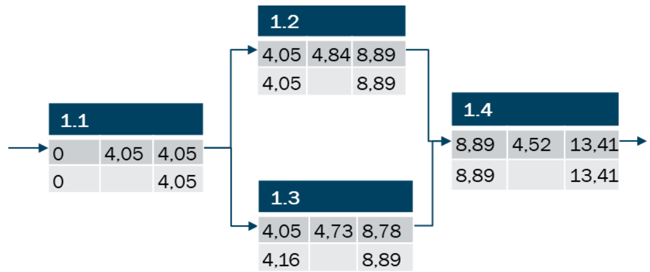


Figure 51: Activity sequencing for the basic scenario FB line assembly

The assembly of the BeewatecSilver has a greater depth of added value and therefore also takes a lot longer than that of the FlexBlue, as the individual parts have to be laboriously screwed together from pipe sections and connecting parts. The prefabrication of the tubes was not considered for this research and tubes were therefore prepared in sufficient quantity for the assembly work in advance. Therefore, the step of commissioning is omitted.

Nr.	Activities BS_Individual WP	
2.0	BS_Individual WP	Assembly stem
		Assembly base
		Wedding, Quality control and packing

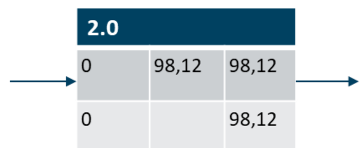


Figure 52: Activity sequencing for the basic scenario BS Individual WP assembly

The line assembly of the BeewatecSilver starts with the two parallel workstations of stem assembly and base assembly. The two workstations are predecessors for the work steps at the final wedding workplace, where the handlebars are connected to the running board, a quality check is carried out and the scooters are packed. During disassembly, which is not part of the investigation but was necessary for the experiments to run smoothly, the scooters are disassembled again and the tubes are pre-commissioned.

Figure 53: Basic Scenario BS_Line Assembly

The following overview shows the associated activity sequencing for the line assembly of the Beewatec Silver Roller type (BS)

Nr.	Activities BS_Line
2.1	FB_Assembly stem
2.2	FB_Assembly base
2.3	FB_Wedding, Quality control and packing

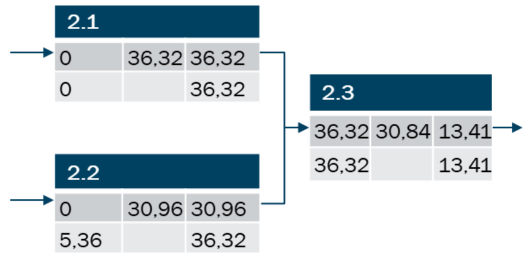


Figure 54: Activity sequencing for the basic scenario BS line assembly

3.2.2 Determination of feasible production scenarios

The decisive information regarding the derivation of different scenarios based on the basic scenarios is, on the one hand, the availability of employees and their qualification for the respective jobs and, on the other hand, the availability of the other resources, in the form of workplace tables and tools.

A qualification matrix makes it possible to find out whether an employee has already been introduced to a job and can perform it. In addition, the availability of the employees can be found. In the following, the qualification matrix and the availability of the employees (P) can be seen for the basic scenarios of the scooter production in the Werk150.

Table 9: Qualification matrix (qualification and availability)

	workplace	P1	P2	P3	P4	P5
Type 1 Line (FlexBlue)	FB_order picking		x	x	x	x
	FB_assembly base	x	x	x		x
	FB_assembly stem	x	x		x	x
	FB_wedding	x	x	x		x
Type 1 Individual workstation	FB_individual wp	x	x	x	x	x
Type 2 Line (BeewatecSilver)	BS_assembly base	x		x	x	x
	BS_assembly stem	x		x	x	x
	BS_wedding	x		x	x	x
Type 2 Individual workstation	BS_individual wp	x	x			

Employee is available at time of consideration

X Employee can perform the activity/ required workplace and machine

The same applies to the components, such as workstation tables, screwdrivers and devices that are necessary for carrying out the various work steps. In the model, these components are combined into workplaces. When designing the production variants, a lack of availability of individual components can make line production or even a first or second individual workplace impossible and thus limits the number of feasible scenario variants. In addition, a statement about flexibility criteria such as routing flexibility can be made from the availability of alternative resources.

Table 10: Component matrix (using the Flex Blue (FB) line assembly as an example)

Workplaces/-steps (Flex Blue)	**Workplace table**	KO01	AP01	AP02	AP03	AP04	AP08	AP09	AP12	**Devices**	CN 01	RO01 - RO09	MP01 - MP05	HW01	KR01	FC1-12; FC13-18; FC19-25	WZ01 - WZ06	VR02 - VR09	VR12-16	VR11	VR17	Air pump
Order picking (KO 01)		Required										Required						Required				
Stem assembly			Required	Alternative			Alternative									Required	Required	Required			Required	
Base assembly					Required	Alternative							Alternative *			Required *	Required	Required				
Wedding								Required	Alternative			Required	Alternative *	Required *				Required		Required		Required
Individual workstation			Required	Alternative	Alternative	Alternative	Alternative	Alternative				Required	Alternative *	Required *			Required	Required		Required	Required	Required

Component required (blue)
Alternative component (orange)
(In the case of several components, alternatives are assigned/marked with *)

A list of the components with an explanation of the abbreviations can be found in the appendix.

3.3 Extended economic appraisal

The decisive factors for the development of the assessment methodology are the characteristics of small-batch production, the horizon under consideration and the desired scope of the decision, as well as the desired information content and its processing. A multidimensional method is chosen to extend the economic evaluation, as this allows for an extension of the dimensionality, i.e. a consideration of additional relevant criteria. It supplements a statically narrowly designed procedure for cost determination, which is sufficient for the comparison of the configured scenarios, since the planned production quantity and thus the revenue is uniform for all scenarios due to the make-to-order characteristic of the small-scale production. Long-term investment decisions are also not considered in the following consideration with the short decision horizon of one day. The choice for a procedure model falls on a cost/effectiveness analytical procedure, which extends an economic efficiency comparison in the form of cost accounting by a decision-oriented procedure for the condensed information processing of additionally relevant effects in the form of a work system value. For the calculation of the extended economic efficiency, therefore, the partial costs are calculated on the one hand, which enable a short-term decision between the different production alternatives (Schlink 2019, p. 142). The tailored partial cost calculation is extended by the work system value (Wiendahl and Wiendahl 2020, p. 238), which enables a utility value comparison of criteria determined with the help of a quantitative literature analysis. Comparable approaches such as the economic value (Bullinger et al. 1997, p. 392) have existed for decades, but have hardly found industrial application so far. The chosen approach is based on the economic value comparison and the work system determination according to (Metzger 1977).

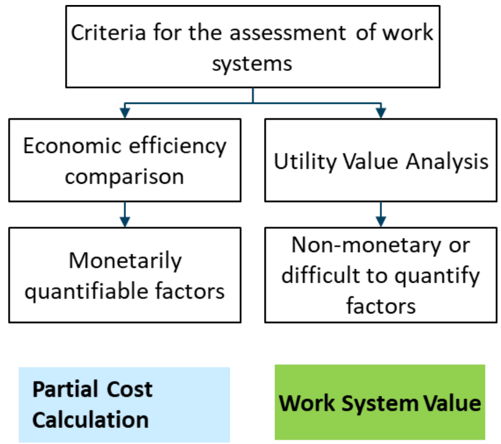


Figure 55: Extended assessment of the economic efficiency [adapted from (Metzger 1977)

3.3.1 Partial cost calculation

Cost accounting forms one of the two pillars for the extended economic efficiency analysis. For a comparison of the selected scenarios, a tailored partial cost calculation is used. Since the decision horizon for the extended economic efficiency calculation is limited to the next (or a few) days in our case, mainly variable costs that differ between the variants are considered for the comparison of production scenarios. The calculation is based on the causation/ polluter pays principle (cost allocation principle). Following (Schlink 2019), a general partial cost calculation is presented below, in which individual, special individual and overhead costs relevant for the time horizon are considered. This approach makes it possible to identify and aggregate relevant cost factors for a defined decision horizon and decision framework and thus also facilitates targeted short-term decisions.

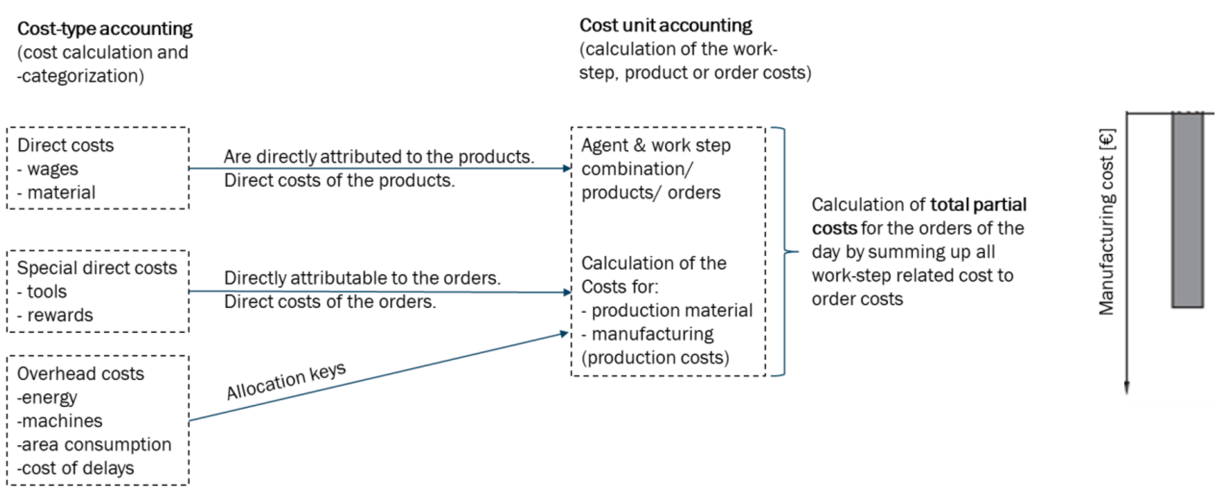


Figure 56: Partial cost accounting, adapted from (Schlink 2019)

Based on the elements presented, the following partial cost calculation was designed for the comparison of possible production system configurations. Aspects such as delivery reliability and rejects and associated costs are relevant to decision-making, but were deliberately excluded from the cost comparison, as they are also considered in the work system value, thus avoiding a double and thus stronger weighting.

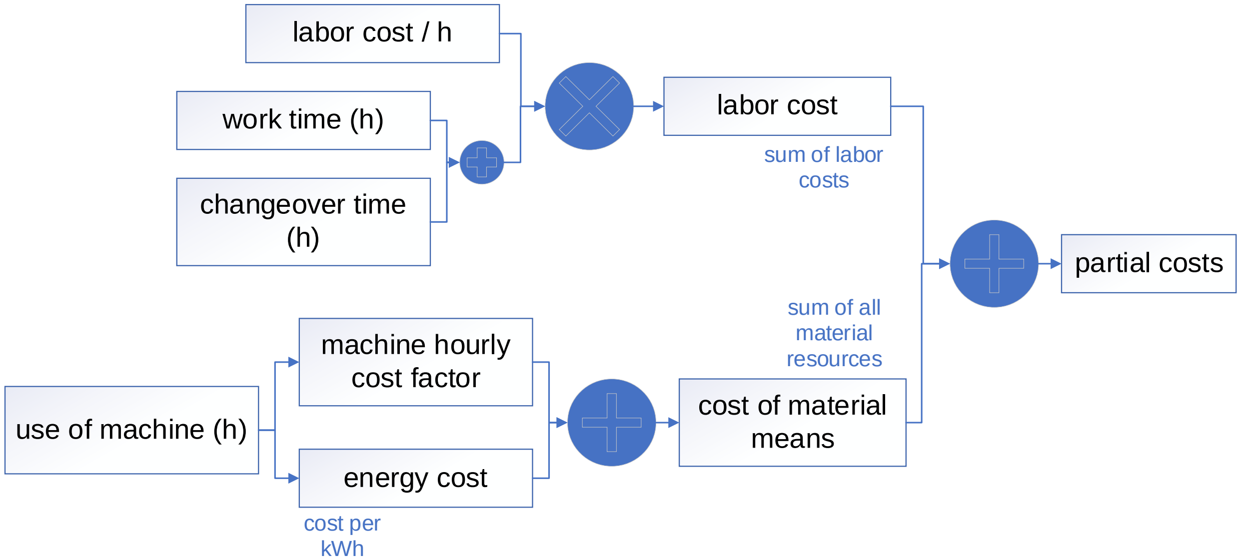


Figure 57: Concept for the comparison of partial costs

Formula for calculating partial cost

$$partial\ cost = labor\ cost + cost\ of\ material\ means$$

$$= changeover\ cost + \sum_{k=1}^{n} d_{WPk} \cdot hw_{P_{WPk}} + \sum_{k=1}^{n} d_{WPk} \cdot (pc_{WP_k} \cdot cpc + mc_{WP_k})$$

$$labor\ cost = changeover\ cost + \sum_{k=1}^{n} d_{WPk} \cdot hw_{P_{WPk}}$$

$$cost\ of\ material\ means = \sum_{k=1}^{n} d_{WPk} \cdot (pc_{WP_k} \cdot cpc + mc_{WP_k})$$

$$WP = work\ place$$
$$n = number\ of\ WP$$
$$d_{WP} = duration\ of\ WP\ [h]$$
$$hw_{P_{WP}} = hourly\ wage\ of\ the\ person\ at\ the\ workplace\ [€]$$
$$pc_{WP} = powerconsumption\ of\ WP\ [kW]$$
$$cpc = cost\ of\ power\ consumption\ per\ kWh\ [€/kWh]$$
$$mc_{WP} = machine\ cost\ of\ WP\ per\ h\ [€/h]$$

During the development of the rating systematic, it was also discussed whether a distinction between active use of the unit (active power consumption) and passive power consumption (creepage current) makes sense. However, initial plausibility calculations have clearly shown that this has no significant influence on the calculation results, so that the occupancy times of the workstations/machines can be used directly for the calculation. If necessary, however, this can be easily adjusted in the model.

Changeover cost (Machine flexibility)

Machine flexibility is defined as the ability to make necessary system changes to switch from one type of product to another (Braglia and Petroni 2000). The set-up effort, which can be measured in labour time, was defined as an indicator for the criterion. A cost value can be calculated via the labour time with the help of employee hourly wages, which can be directly aggregated in monetary terms. In the implemented calculation model, empirical values from a qualitative study in the Werk150 on the time required for setting up the workplaces serve as a reference. For set-up processes where it depends strongly on the set-up from which the set-up process is carried out, it makes sense to define a neutral position and to include the set-up effort from a neutral position and back to the neutral position for each workstation in the model in order to take the current status of the factory into account. In the considered use case in the Werk150, the effort varies only slightly with the previous set-up, so that an exclusive consideration of the set-up effort is sufficient. The calculation of the changeover costs is illustrated below with the help of a simplified example.

$$changeover\ cost\ (machine\ flexibility\ mf) = \sum_{k=1}^{n} sd_{WP_k} \cdot hw_{P_{WPk}}$$

$$sd_{WP} = set\ up\ duration\ for\ WP\ [h]$$
$$hw_{P_{WP}} = hourly\ wage\ of\ person\ setting\ up\ the\ WP\ [€/h]$$

Example calculation:

Table 11: Set-up effort and employee responsibility

Work place (WP)	Time required to set up the WP (sd_{WP}) [min]	Person in charge (by default) (P_{WP})
WP1	10	P1
WP2	10	P1
WP3	10	P1
WP4	20	P1

Table 12: Hourly wages

Person (P)	Wage (hw) [€/h]
P1	20
P2	15
P3	25
P4	35

Changeover cost $(mf) = \frac{sd_{WP1}}{60} \cdot hw_{P_{WP1}} + \frac{sd_{WP2}}{60} \cdot hw_{P_{WP2}} + \frac{sd_{WP3}}{60} \cdot hw_{P_{WP3}} + \frac{sd_{WP4}}{60} \cdot hw_{P_{WP4}}$

Changeover cost $(mf) = \frac{10\ min}{60} \cdot 20\ €/h + \frac{10\ min}{60} \cdot 20\ €/h + \frac{10min}{60} \cdot 20€/h + \frac{20min}{60} \cdot 20€/h =$ 16,67€

CO_2 emissions (ecology)

The criterion of ecology, which is defined as CO_2 emissions in this analysis, is similar to the costs incurred. Although no direct aggregation of the CO_2 emissions in monetary currency is carried out, these are absolute deficits caused by production. Therefore, the polluter pays principle is also applied to the CO_2 emissions. If CO_2 credit systems become established in the future, with which emissions caused with the help of certificates can be offset, aggregation with the costs would also be conceivable.

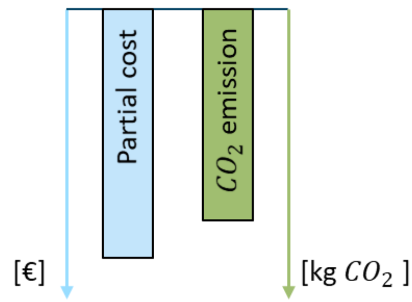


Figure 58: Partial cost and CO_2 Emission on the Input side of the extended economic efficiency calculation

CO_2 emissions are calculated on the basis of electricity consumption and the usual CO_2 emissions per kWh for the location of the machine. The German power mix (gpm) (as of 2020) is 0.4 (kg·CO_2)/kWh (Federal Environment Agency). This value is stored in the database of the description model. In the future, the value could also be updated automatically with the help of Oracles, which access data from the Federal Environment Agency, for example. The electricity mix factor plays a role in the calculation if alternative energy sources are also available for scenarios. Since CO_2 emissions are not an absolute and not an ordinal quantity, as is the case with the other criteria, they are considered as a separate cost factor on the input side in the scenario evaluation, so that in addition to the costs in the national currency, the CO_2 costs of the scenario are also given in kgCO_2.

Initially, it was planned to include the creeping current in the consumed electricity in addition to the active electricity use, but it turned out that this is marginal and thus negligible for our consideration.

$$Ecology\ (ec) = pm \cdot \sum_{k=1}^{n} pc_{WP_k} \cdot d_{WP_k}$$

$$gpm = german\ power\ mix\ [kgCO_2/kWh]$$
$$pc_{WP} = power\ consumption\ at\ WP\ [kW]$$
$$d_{WP} = occupancy\ time\ at\ WP\ [h]$$

Example calculation:

Table 13: Workplace times from the simulation and machine hourly rate (per WP)

Work place (WP)	Duration of WP (d) [min]	Power consumption (pc) (machine/ WP rate) [kW]
WP1	45	1
WP2	50	1
WP3	60	1
WP4	50	1

$$Ecology\ (ec) = pm\ \cdot (pc_{WP_1} \cdot \frac{d_{WP_1}}{60} + pc_{WP_2} \cdot \frac{d_{WP_2}}{60} + pc_{WP_3} \cdot \frac{d_{WP_3}}{60} + pc_{WP_4} \cdot \frac{d_{WP_4}}{60})$$

$$ec = 0{,}4\ kg\ CO_2/\ kWh\ \cdot (1\ kW \cdot \frac{45\ min}{60} + 1kW \cdot \frac{50\ min}{60} + 1kW \cdot \frac{60\ min}{60} + 1\ kW \cdot \frac{50\ min}{60} = 1{,}4$$ kg CO_2

The following chapter explains the systematic derivation of the assessment criteria of the work system value. The criteria identified as relevant, ecology and machine flexibility, unlike the other criteria, are not included in the work system value but exclusively on the input side of the extended economic efficiency calculation in order to avoid double aggregation.

3.3.2 Work system value

To calculate the work system value, a utility analysis of weighted criteria is carried out, based on the description by (Ney 2006).

Equation 1: Utility value analysis with transformation and weighting of work system value criteria (adapted from (Ney 2006))

$$\text{Work system value (wsv)} = \sum_{i=1}^{m} [g_i * wsv(k_i)]$$

g_i	=	Weighting of the target criterion
k_i	=	Characteristics of the target criterion
$wsv(k_i)$	=	Transformation function for the wsv target criterion
m	=	Number of criteria

As the formula of the utility value according to (Ney 2006) describes, the different criteria are first brought into a uniform form and size with the help of a transformation function and then individually weighted. The assessment procedure follows the ideal-typical phase model of an assessment according to (Reichwald et al. 1996).

1. Target setting	2. Generation of measures, networking and synergy effects	3. Holistic assessment
Definition of relevant goals	Detection of interdependencies	Target weighting
Derivation of subgoals	Identification of measures to influence the subgoals	Assessment of the measures with regard to the achievement of targets
Operationalization of subgoals	Recording the compatibility of the measures with each other	Selection decision

Figure 59: Ideal-typical phase model of an assessment (Reichwald et al. 1996)

First, the objectives of the assessment are identified. In this research project, this is done on the basis of the state of the art in science and technology, which is made available with the help of literature from the areas of the design and evaluation of CPPS and of industrial and social goals, which are made available with the help of CSR reports from companies. The text sources mentioned are selected qualitatively in the first step. They are then analysed quantitatively. Based on these results, a qualitative assessment is made as to whether the respective aspects are relevant for consideration and whether they differ between the possible scenario configurations. Once the assessment criteria are defined, appropriate associated indicators are defined, which allow operationalisation with the help of clear measurement variables. The choice of indicators and the development of a calculation logic is based on a targeted qualitative literature analysis. Subsequently, target dependencies are recorded in order to identify problems and compound effects.

Multi-step literature research to derive criteria and their calculation

This section describes the procedure chosen to derive and update the work system value criteria. Apart from ensuring comprehensibility in the development of the evaluation logic, this section also serves to present an approach with which criteria collections can be derived and operationalised in relation to different applications. The chosen approach consists of a three-step literature analysis, in which first a qualitative selection of literature is made. In the second step, the texts are examined with the help of software for quantitative literature analysis. Finally, the results of the quantitative analysis are brought into the context of work system value assessment for small-scale production with the help of qualitative findings in order to define criteria and develop a calculation logic of the criteria with the help of indicators.

Qualitative review and selection of relevant literature

The semi-structured literature analysis described in the first chapter is applied in the first qualitative part of the literature analysis for criteria development. Different channels, such as university libraries, digital scientific databases and journal rankings are used in the search for literature sources. Key search terms relate to the design and evaluation of CPPS. When selecting literature works, the texts are approached step by step, from the heading to the abstract, to the entire text. Texts classified as relevant are collected for the next step, quantitative word frequency-based analysis. A total of 82 text sources were selected, dealing with topics of CPPS design and evaluation, to be included in the subsequent quantitative investigation.

Quantitative review of rating criteria

In the phase for defining the work system value criteria, which are to extend the classical cost accounting, a quantitative literature analysis is carried out to identify the topic areas relevant for evaluation. The analysis of the words and their frequency also serves as an indication of the importance of the topic area and their priority. Below are two alternative tools and procedures that could be useful for this purpose.

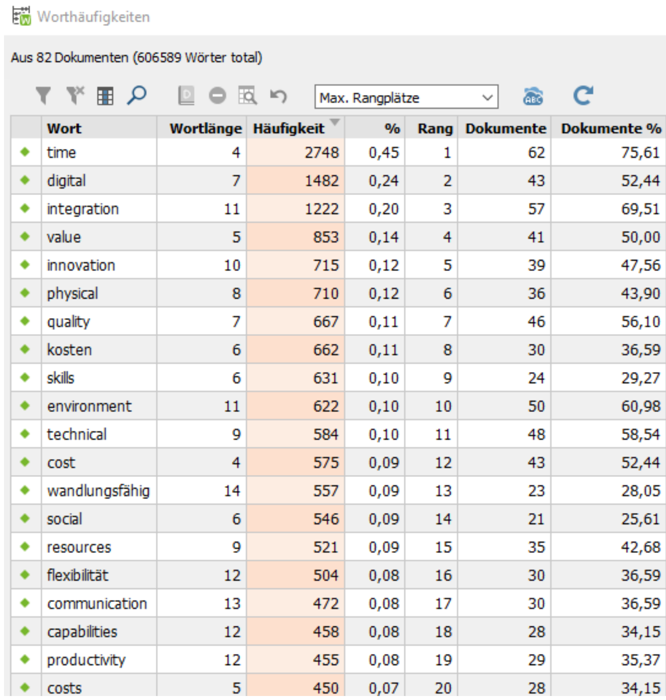
One way to identify relevant aspects of evaluation is to visualise frequent words using a word cloud. This can be implemented with the help of Python, for example. The advantage of this is the freedom of design, as shown in the following diagram, which was generated on the basis of a literature source by Deuse on CPPS (Deuse et al. 2015).

Figure 60: Generated in Python from (Deuse et al. 2015)

However, some disadvantages can also be identified. For example, it is immediately obvious that the words appear in German and a thematic grouping in English and with other words is not possible. In addition, it is difficult to include more than one text source in the analysis with this application, which limits the general validity of the information about the state of the art. Lemmatisation, i.e. the reduction of the word to its basic form in order to avoid duplications, is also not easily possible, as is the omission of filler words that occur frequently in the language but have no relevance to the topic of the design and evaluation of CPPS. The next illustration shows a word cloud depicting the results of a quantitative literature analysis of 52 text sources in the field of CPPS design and evaluation using the analysis in MAXDictio, an application of the MAXQDA software. With MAXQDA it is easy to look at several text sources at the same time, to exclude irrelevant words and to lemmatise words and form thematic categories.

Figure 61: Generated in MAXQDA (MAXDictio) from 52 text sources on the topics on design and assement of CPPS & CSR reports)

MAXQDA is chosen as the tool for the quantitative literature analysis, as the achievable analysis result is considered to be more meaningful. After the selection of the analysis tool, the actual analysis is started, which refers to text sources on the design and evaluation of CPPS, as well as CSR reports and sustainability goals that promise information on industrial, corporate and social goals. The analysis was based on 82 text sources with a total of over 600,000 words. After the initial analysis of word frequency, words deemed irrelevant were marked and not considered further in the analysis. These include, in particular, frequently occurring pronouns, particles, filler and linking words, which do not provide any added value in terms of content.



Worthäufigkeiten

Aus 82 Dokumenten (606589 Wörter total)

Wort	Wortlänge	Häufigkeit	%	Rang	Dokumente	Dokumente %
time	4	2748	0,45	1	62	75,61
digital	7	1482	0,24	2	43	52,44
integration	11	1222	0,20	3	57	69,51
value	5	853	0,14	4	41	50,00
innovation	10	715	0,12	5	39	47,56
physical	8	710	0,12	6	36	43,90
quality	7	667	0,11	7	46	56,10
kosten	6	662	0,11	8	30	36,59
skills	6	631	0,10	9	24	29,27
environment	11	622	0,10	10	50	60,98
technical	9	584	0,10	11	48	58,54
cost	4	575	0,09	12	43	52,44
wandlungsfähig	14	557	0,09	13	23	28,05
social	6	546	0,09	14	21	25,61
resources	9	521	0,09	15	35	42,68
flexibilität	12	504	0,08	16	30	36,59
communication	13	472	0,08	17	30	36,59
capabilities	12	458	0,08	18	28	34,15
productivity	12	455	0,08	19	29	35,37
costs	5	450	0,07	20	28	34,15

Figure 62: Word frequency analysis in MAXDictio using 82 text sources

The next step was to try to form thematic groups in order to roughly summarise the contents. The allocation to the groups was a first attempt to form clusters, which, however, already has a qualitative character due to the human bias. The formation of clusters was only partially effective at this point and only served to avoid duplication of content.

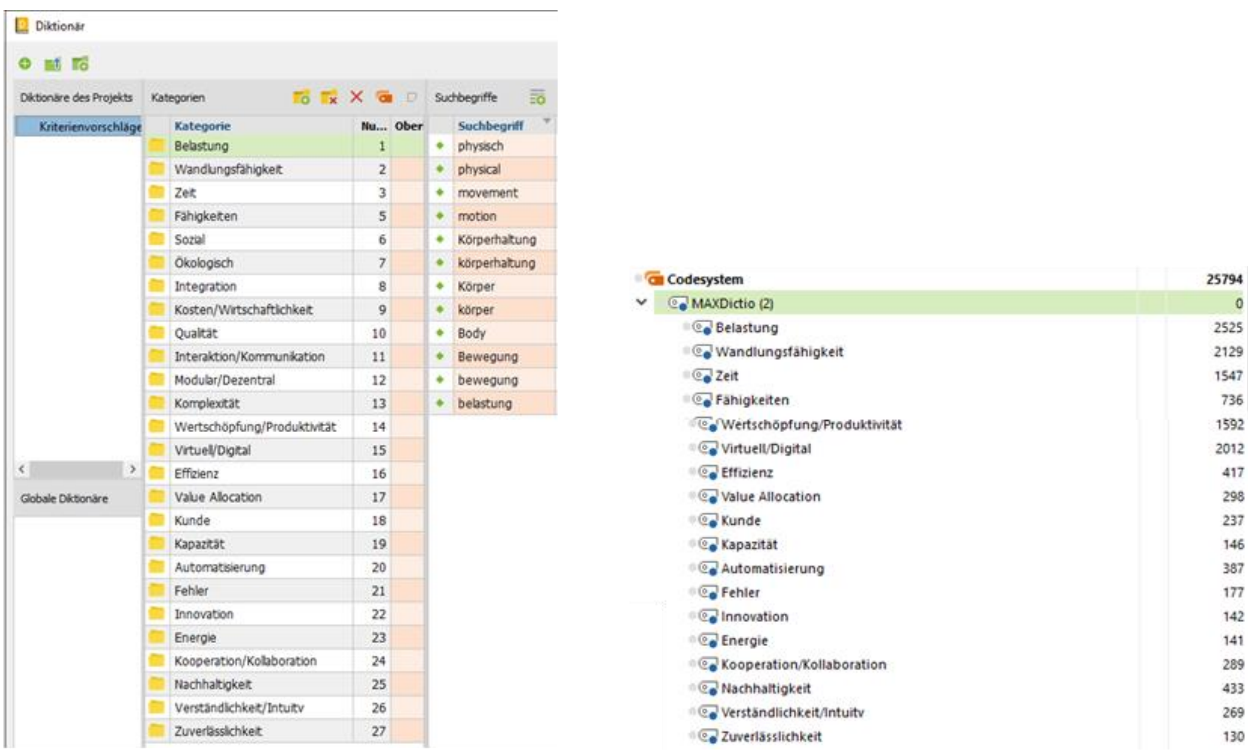


Figure 63: Clustering of search terms to summarise thematic areas

The quantitative literature analysis showed the frequency of words and thus an indication of words with high significance became apparent.

Qualitative review for criteria operationalization

Based on this, the most frequent words were assessed with the help of a qualitative literature analysis. Multiple discussions of an expert group consisting of 2 students and 2 supervising professors allowed to define the final evaluation criteria and related indicators for their calculation. For the selection of the criteria, it is decisive whether aspects change with a variation of the scenario or whether a direct connection can be established between the word and the possible production scenarios. For the word "customer", for example, no direct connection to the production scenarios can be derived. The defined work system value criteria are shown and defined in the following table. They are the result of the multi-stage literature analysis, in which 82 qualitatively selected text sources were approached with the help of a quantitative word frequency analysis, in order to finally derive the work system value criteria with the help of findings from a qualitative literature analysis and expert assessment.

Table 14: Overview of work system criteria

Criteria (k_i)	Definition
Physical stress	The workload is the totality of the detectable influences in the work system, which affect humans (DIN 33400:1983-10). Physical stress can be understood as the individual perception of the affecting workload. (Knauth)
Mental stress	The totality of all detectable influences that come from outside and have a psychological effect on people. Mental stress can be considered as the psychological impact of workload on the individual, including both mental and emotional components. (DIN EN ISO 10075-1 (2001)) (Schmidt and Thews 1977)
Error potential	Error potential describes the likelihood of the occurrence of irregularities where the product does not meet strict quality standards (Pawlikowski)
Competence-fit	Competence describes the ability for self-organized, creative action in open problem and decision situations. The competence-fit criterion combines employee preferences and the fulfilment of requirements for selected competence types from the KodeX atlas (Faix 2012).
Delivery reliability	Delivery reliability as the on-time delivery of the ordered products is indicated by number of types of products (proportion) that can be produced within a defined period, measured in terms of value added.
Capacity utilisation	The capacity of human beings and resources is given by their capacity to perform. The quantitative capacity of the work system is determined by the number, time and duration of available people and resources. (Krüger 2004)
Process flexibility	Process flexibility describes the ability of the production system to produce a given set of product types and variants without changing the setup or equipment (Braglia and Petroni 2000; ElMaraghy 2005)
Routing flexibility	Routing flexibility is defined as the ability to manufacture parts via several routes or to perform different operations on more than one machine (Zammori et al. 2011)
Machine flexibility*	The ability to make the necessary changes to machines to switch from one set of parts to another (Braglia and Petroni 2000)

Ecology*	Environmental compatibility through renewability of raw materials and non-damage to nature and environment, e.g. caused by emissions.

*Considered on the input side (cost accounting and emissions)

In the following, the developed calculation formulas for the different criteria are presented. In some cases, the workplaces are assessed individually and weighted against the other workplaces in order to obtain a comparable statement about the overall scenario. For the weighting of the assessment of each workplace on the overall scenario, depending on the type of criterion, a weighting is applied according to the duration of the activity or according to the added value of the activity at the respective workplace. For people-oriented criteria, weighting is based on the duration of the activity, and for process-oriented criteria, weighting is based on the value added.

Physical and mental stress

Stress, as a subjective perception of strain, which is already difficult to measure, poses a challenge when it comes to operationalising the criteria of physical and mental stress. Nevertheless, stress and not strain was very deliberately defined as a criterion, as only this reflects the well-being of the employee. The most meaningful way to find out about stress is to ask the people concerned about their subjective perception. These empirical values can then serve as an indicator for future situations. For this reason, tests are carried out in the factory150 in which the employees give their assessment of the stress for each workplace at which they work. Therefore, post-hoc lists for combinations of employees and workplaces and the experience values of the respective physical and mental stress serve as a basis for the assessment of stress. For the two criteria, mental and physical stress, the employees were asked after each shift about their subjective assessment of the stress and requested to rate it on an ordinal scale of 1-5 (high stress - low stress). In the evaluation system, the standard approach for calculating mental and physical stress is to use an experience matrix with mean values from previous shifts for each possible combination of employee and workplace. Since all possible combinations of employee and workplace in the qualification matrix, which are thus permitted for employee allocation, have already been tested, data are already available with the help of which the evaluation model can be developed. The calculation of the total stress values for the criteria physical stress and mental stress are weighted per task according to the share of the time duration of the respective workplace in the entire assembly process. Since the division of labour in the example production of the lines and individual workplaces was selected so that each workstation makes the same contribution to the value added, the calculation is simplified. Alternatively, in the case of combinations in which no empirical values are yet available, a machine learning programme was written which predicts the values for new combinations using empirical values available in CSV format. If a real scenario is to be evaluated, the measured body reactions can also contribute to improving the prediction of the employees' subjective assessment. In the following, a calculation example is carried out to illustrate in principle the determination of the stress criteria and to show the sources of information. The values are freely chosen and it is attempted to keep the calculation simple in order to present the basic procedure.

Table 15: Example of workplace times from the occupancy simulation and allocation of staff allocation

Work place (WP)	Duration (d) [min]	Person (P)
WP1	45	P1
WP2	50	P3
WP3	60	P2
WP4	50	P4

Since the workplace times correspond to the employee times that are allocated to the workplaces, an approach is chosen for the concrete implementation that first simulates the workplace times and only in the subsequent step is an employee allocation made. This enables a high degree of scenario variability with a manageable simulation effort.

Table 16: Example of a table of mean values from the database on mental stress (ms) (1-5)

Person (P) Arbeitsplatz (WP)	P1	P2	P3	P4	…
WP1	5	2			
WP2		3	4	5	
WP3		3	4	2	
WP4	5	1		3	
…					

Calculation

$$mental\ stress\ (ms) = \frac{\sum_{k=1}^{n} ms_{WP_k} \cdot d_{WPk}}{\sum_{k=1}^{n} d_{WPk}}$$

$$ms_{WP} = mental\ stress\ at\ the\ workplace$$

$$d_{WP} = duration\ of\ WP\ [min]$$

In words, the calculation provides for the weighting of employee stress, as a personal work system value criterion, according to time, since this is more important for the well-being of employees than value creation. For this purpose, the sum of the products of employee stress at the workplace and employee time at the workplace is divided by the sum of the work durations. The following is an example of the calculation.

$$mental\ stress\ (ms) = \frac{ms_{WP1} \cdot d_1 + ms_{WP2} \cdot d_2 + ms_{WP3} \cdot d_3 + ms_{WP4} \cdot d_4}{d_1 + d_2 + d_3 + d_4}$$

$$mental\ stress\ (ms) = \frac{5 \cdot 45\ min + 4 \cdot 50\ min + 3 \cdot 60\ min + 3 \cdot 50\ min}{45\ min + 50\ min + 60\ min + 50\ min} = 3{,}68$$

Since the utility value analysis according to Metzger (1977) provides for a transformation of the criteria into a uniform form, the result, which until now has been classified on an ordinal scale from 1 (very stressful/unpleasant) to 5 (low stress/pleasant), will be converted into a percentage value.

$$wsv(ms) = ms \cdot \frac{100}{5}$$

$$wsv(ms) = 3{,}68 \cdot \frac{100}{5} = 73{,}6\%$$

In the fictitious example, the total mental stress would be 73.6%. The procedure for physical stress (ps) is carried out analogously on the basis of collected empirical values for physical stress.

Error potential

The total error potential results from the expected reject rate and is calculated per order from the reject ratios of the workplaces used. This is done by weighting the individual empirical values of the reject rates per workplace according to the share of the added value of the respective workplace in the entire assembly process. Since the division of labour in the example production of the lines and individual workstations was selected so that each workstation makes the same contribution to the value added, the calculation is simplified. The data on error probability, like the data on mental and physical stress, were not yet evident from the occupancy planning. Therefore, these data were also collected during experiments. For the prediction of the error potential, analogous to the stress criteria, experience values of the individual employees at the workplaces are assumed as expected future values. This is the case at least until the modelling approach developed with the help of the continuous learning process has sufficient data to enable meaningful and reliable forecasts with the help of machine learning algorithms.

Calculation example:

For tomorrow there is an order with the following quantities per product type:

Orders product type 1 (q_1): 20 pieces

Orders product type 2 (q_2): 40 pieces

Table 17: Value added of the product types

Product type (Pt)	Value added per piece (va/pcs)	Value added of product type for order (va_{Pt})
1	30 money unit (MU)	600 MU
2	12 MU	480 MU

Product type 1 is distributed to workplaces WP1 - WP3 in the occupancy planning and is assembled in line. The value added per product is 30 monetary units (MU). The value added per unit is distributed evenly among the workplaces, so that a value added of 10 MU is assumed per workplace. Product type 2 is produced at WP4 in single workplace assembly and the value added is 12MU.

Table 18: Example of value added per workplace

Work place (WP)	Value added pro WP per piece (va_{WP}/ pcs)	Quantity product type 2	Quantity product type 1	Value added per WP (va_{WP})
WP1	10 MU	20	0	200 MU
WP2	10 MU	20	0	200 MU
WP3	10 MU	20	0	200 MU
WP4	12 MU	0	40	480 MU

$$mit: Value\ added\ per\ WP\ (va_{WP}) = \sum_{k=1}^{n} (va_{WP}/\text{pcs})_{WP_k} \cdot q$$

$$q = quantity\ [pcs]$$

Table 19: Example of employee allocation

Work place (WP)	Person (P)
WP1	P1
WP2	P3
WP3	P2
WP4	P4

As with the criterion for employee stress, employees are allocated to the workplaces. For the fictitious example scenario, the allocation remains unchanged. The following table shows an example of the information from mean values of documented reject rates from past assembly trials.

Table 20: Example of a table of mean values from the database for the recorded reject rate (rr) (0-1)

Person (P) Work place (WP)	P1	P2	P3	P4	…
WP1	0,12	0			
WP2		0,2	0,2	0,35	
WP3		0,08	1	0	
WP4	0,4	0,1		0	
…					

$$error\ potential\ (ep) = \frac{\sum_{k=1}^{n} rr_{WP_k} \cdot va_{WP_k}}{\sum_{k=1}^{n} va_{WP_k}}$$

$$rr = rejection\ rate$$

Since a rating from bad to good must be made on a uniform scale in order to aggregate the criteria, the Error Potential criterion is transformed into % using the following formula. $wsv(ep)$ of 100% then corresponds to the target value of 0% error potential (reject potential):

$$wsv(ep) = (1 - ep) \cdot 100$$

Competence-fit

The competence fit as a work system value criterion must be clearly distinguished from the employee qualification, which is a prerequisite for assigning an employee to a workplace. The aim of the competence fit is, on the one hand, to compare the workplace requirements of the employee with the competence profile of the assigned employee for selected types of competence. On the other hand, the employee's preference for a particular workplace will be looked at, in order to consider both the interest and the development opportunities of the employee. This results in two parts that together constituted the competence fit criterion. The competence delta (c△) and the preference (p). The overall calculation of the competence fit results by default from a 50% weighting of p and c△.

$$Competence - fit\ (cf) = \frac{wsv(p)\ +\ wsv(c\ \triangle)}{2}$$

Calculation of Preference (p)

The first part of the competence fit, is hereafter referred to as preference (p), as it assesses the fulfilment of the employee's preference for the occupation scenario. The preference is chosen by the employee and can have different motivations such as enjoyment of the job, a desire for further training or a search for a challenge. Since it is an aspect that relates to the employee, the values of the individual employees are weighted according to the working hours. The calculation is analogous to the calculation of stress.

Table 21: Example of surveyed employee preferences p (1-5)

Person (P) Work place (WP)	P1	P2	P3	P4	…
WP1	4	4	4	4	

WP2	5	4	5	5	
WP3	3	3	4	5	
WP4	1	4	2	2	
…					

Calculation

$$preference\ (p) = \frac{\sum_{k=1}^{n} p_{WP_k} \cdot d_{WPk}}{\sum_{k=1}^{n} d_{WPk}}$$

$$p_{\mathrm{WP}} = preference\ value\ at\ the\ WP$$

The result for the preference p must finally be transformed into a proportion value (%) to enable a uniform form and thus an aggregation of the criterion with other ASW criteria. The scale of preference goes from 1 (low) to 5 (high). A p = 5 would correspond to a criteria fulfilment of 100%. This results in the following transformation function.

$$wsv(p) = p \cdot \frac{100}{5}$$

Calculation of competence delta (c△)

The competence delta (c△) describes the deviation between the requirements profile and the employee competence profile, weighted according to the value-added share of the activities. Both a lack of competence and overqualification are undesirable. The better the profiles match, the higher the value for the competence delta sub-criterion (c△). Faix (2012) presents the KodeX atlas, a collection of competences described in the previous chapter. This approach is taken up for the calculation of the competence-delta part of the competence fit, i.e. the aspect of the match between the competence requirement and the employee profile, and implemented in a similar form in order to obtain a percentage estimate of the fulfilment of the competence for each scenario.

For selected competence types from the KodeX Competence Atlas by Faix (2012), both the requirement profiles of the work steps and the competence profiles of the employees are classified on a scale of 1 (low) - 5 (high). The requirement profiles of the workplaces are expert assessments, while the competence profiles of the employees in the presented concept are based on a self-assessment, which could, however, also be extended to include further assessments. For the constellations resulting from the allocation of employees to workplaces, the individual requirement profile values are compared with those of the competence profiles. A match between the profiles indicates an appropriate allocation of competencies, without over- or under-demanding. The following table shows sample values to facilitate an explanation of the concept.

Table 22: Work place requirements and profile of person for different competence types

		WP1	WP2	WP3	WP4	WP n		P 1	P 2	P 3	P4	P x
Competence typ (c)		cr_{WP1}	cr_{WP2}	cr_{WP3}	cr_{WP4}	cr_{WPn}		$ce_{P_{WP1}}$	$ce_{P_{WP3}}$	$ce_{P_{WP2}}$	$ce_{P_{WP4}}$	$ce_{P_{WPn}}$
Personal responsi bility	c_1	$c_1 r_{WP1}$ 1	1	1	4			5	5	3	3	
Commit ment	c_2	4	4	4	3			3	5	4	5	

Adaptability	c_3	3	2	2	2			4	3	2	1	
Diligence	c_4	4	4	4	4			3	3	1	5	
Problem-solving ability	c_5	2	3	2	5			2,5	2	2	3	
…	c_m											

$$\mathrm{c} = competence\ typ$$

$$cr_{WP} = competence\ requirement\ at\ WP$$

$$ce_{P_{WP}} = competence\ typ\ estimation\ of\ person\ at\ WP$$

In addition, the value added is calculated analogously to the error potential with:

$$value\ added\ per\ WP\ (va_{WP}) = \sum_{k=1}^{n} (va_{WP}/\mathrm{pcs})_{WP_k} \cdot q$$

$$q = quantity\ [pcs]$$

The formula for calculating the competence delta (c△) is as follows:

$$competence\ delta\ (c\ \triangle) = \frac{\sum_{k=1}^{n}\sum_{j=1}^{m} |c_j r_{WP_k} - c_j e_{P_{WPk}}| \cdot va_{WP_k}}{m\ \cdot\ \sum_{k=1}^{n} va_{WP_k}}$$

$$c_1 r_{WP1} = \ requirement\ of\ competence\ type\ 1\ at\ workplace\ 1\ (WP1)$$

$$c_1 e_{P_{WP1}} = \ fullfillment\ estimation\ \ of\ competence\ type\ 1\ by\ the\ person\ at\ WP1$$

$$va_{WP} = \ Value\ added\ per\ WP$$

$$n = number\ of\ WP$$

$$m = number\ of\ c$$

The calculated value of the competence delta (c△) is transformed into the unitary aggregation form in % using the following formula.

$$wsv(c\ \triangle) = (1 - \frac{c\ \triangle}{5}) \cdot 100$$

Delivery Reliability

The criterion delivery reliability describes the delivery of the ordered product types within the specified delivery period, weighted according to value added. If all orders are produced within the deadline, the delivery reliability is completely fulfilled. Otherwise, the proportion added value of product types completed on time is assessed. Whether a product type can be delivered to the customer on time depends on whether the ordered quantity has been completely assembled by a defined target date. For the single workstation, this is fulfilled if the end time of the single workstation is before the target date. For line assembly, this is fulfilled if the last workstation in the precedence relationship has completed the ordered quantity before the target date.

- Orders product type 1 (q_1): 20 pieces
- Orders product type 2 (q_2): 40 pieces

Table 23: Example of information on value added and delivery reliability of product types

Product type (Pt)	Last WP in the precedence sequence of product type (lWP_{Pt})	Value added per piece (va/pcs)	Value added of Pt (va_{Pt})	End date of last WP in the precedence sequence of product type (end of lWP_{Pt})	Target Delivery date of the product type	Timely delivery of product type (td_{Pt}) [yes (1)/no (0)]
1	WP3	30 MU	600 MU	23.12.21 12:00	23.12.21 15:00	1
2	WP4	12 MU	480 MU	10.01.22 9:15	23.12.21 15:00	0

First, it is checked whether a timely delivery of product type (td_{Pt}) is possible based on the simulation times. The product type is then marked yes [1] if it is ready on time and no [0] if it is not. The delivery reliability is calculated as follows:

$$delivery\ reliability\ (dr) = \frac{\sum_{k=1}^{n} va_{Pt_k} \cdot td_{Pt_k}}{\sum_{k=1}^{n} va_{Pt_k}}$$

$$va_{Pt_k} = value\ added\ by\ product\ type$$

$$td_{Pt} = timely\ delivery\ of\ product\ type\ [y(1)/n(0)]$$

$$asw(dr) = dr \cdot 100$$

Capacity utilisation

The capacity of human beings and resources is given by their capacity to perform. The quantitative capacity of the work system is determined by the number, time and duration of available people and resources. (Krüger 2004) The capacity is provided directly by the occupancy simulation.

Routing flexibility

Routing flexibility describes the degree of freedom to produce a product on different routes, i.e. the possibility to carry out work steps on more than one machine. The greater the proportion of value-added from workplaces that can be replaced by alternative resources, the higher the score for the criterion routing flexibility.

Table 24: Example of value added per workplace and alternative resource availability

Work place (WP)	Value added per piece (va_{WP}/pcs)	Quantity Product type 2	Quantity Product type 1	Value added per WP (va_{WP})	Alternative resource available at WP (ar_{WP_k}) [yes (1)/no (0)]
WP1	10 MU	20	0	200 MU	1
WP2	10 MU	20	0	200 MU	1

WP3	10 MU	20	0	200 MU	0
WP4	12 MU	0	40	480 MU	1

The value added per WP is calculated according to the same principle as presented for the error potential. For the activities at each workstation, the availability of an alternative resource is checked before the assessment. If an alternative resource is available to carry out the activity, the work step at the workstation is marked with yes (1) and if no alternative resource is available with no (0). The routing flexibility is calculated with the following formula.

$$routing\ flexibility\ (rf) = \frac{\sum_{k=1}^{n} ar_{WP_k} \cdot va_{WP_k}}{\sum_{k=1}^{n} va_{WP_k}}$$

$$ar_{WP_1} = alternative\ resource\ available\ at\ WP1\ [yes(1)/no(0)]$$

$$asw(rf) = rf \cdot 100$$

Process Flexibility

This type of flexibility describes the value-added share of the workstations at which more than 1 or, in the example, all product types can be produced without making changes to the setup. In the example, both product type 1 and 2 can be assembled at WP4 without any set-up effort.

Table 25: Example of value added per workplace and alternative resource availability

Work place (WP)	Value added per piece (va_{WP}/pcs)	Quantity product type 2	Quantity product type 1	Value added per WP (va_{WP})	At WP more than one Product type can be produced (ap_{WP_k}) [yes (1)/ no (0)]
WP1	10 MU	20	0	200 MU	0
WP2	10 MU	20	0	200 MU	0
WP3	10 MU	20	0	200 MU	0
WP4	12 MU	0	40	480 MU	1

For each workplace it is known whether more than 1 product type can be produced without changes. If the production of an alternative product type that is produced in the observation horizon is possible, the workplace is marked with yes (1) and if only the current product type can be produced, it is marked with no (0). The process flexibility is calculated with the following formula.

$$prozess\ flexibility\ (pf) = \frac{\sum_{k=1}^{n} ap_{WP_k} \cdot va_{WP_k}}{\sum_{k=1}^{n} va_{WP_k}}$$

$$ap_{WP_1} = alternative\ producttyp\ produceable\ at\ WP1\ [yes(1)/no(0)]$$

$$asw(pf) = rf \cdot 100$$

Machine Flexibility

Braglia (2000) defines machine flexibility as the ability to make necessary system changes to switch from one type of product to another.

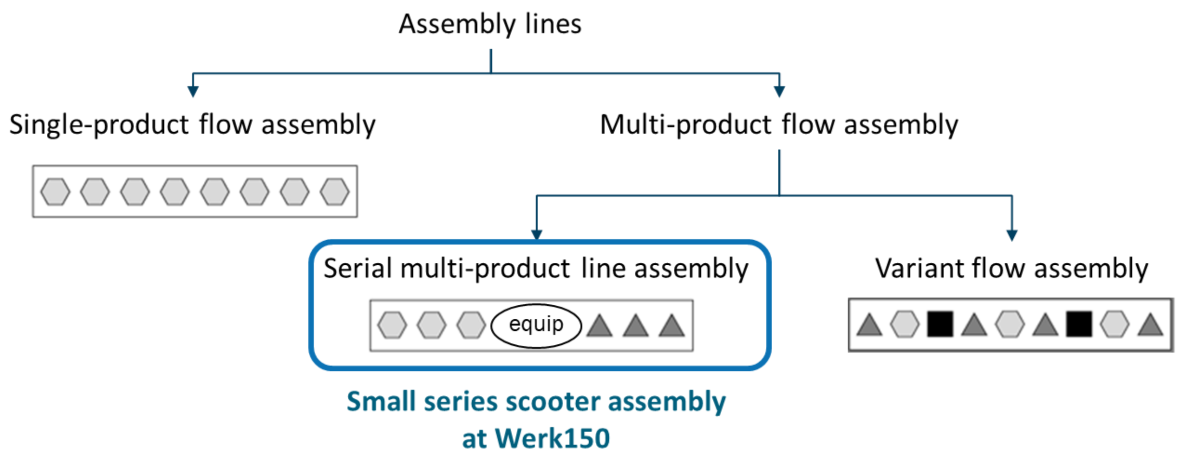


Figure 64: Classification of flow assembly lines (Pröpster 2015) (based on Scholl (1999, p.7), Boysen (2005, p. 11))

As marked in the illustration based on Pröpster (2015), the line production of small batch production considered in the Werk150 is a serial multi-product flow assembly. This means that different products can be manufactured, but a set-up process may be necessary to change over from one product type to another. If sufficient resources are available, set-up can be dispensed with. In our example, the machine flexibility can be defined by the set-up effort for a change of the set-up, which causes costs, but can also have an impact on the delivery date. In order to avoid an unintentional multiple use of a criterion, as with the criterion of error potential or delivery reliability, it was decided to evaluate the machine flexibility exclusively within the framework of cost accounting and, if necessary, to let it flow into the calculation of delivery reliability.

Ecology

The criterion of ecology generally includes environmental friendliness through the renewability of raw materials and the absence of damage to nature and the environment. For the comparison of the scenarios, however, it was defined to be limited to the emissions associated with the electricity consumed in production in the form of CO_2 emissions and to be compared between the scenarios. The criterion of ecology is similar to that of machine flexibility. Even if a direct aggregation of the CO_2emissions in euros is not possible, the polluter-pays principle can be applied to the CO_2 emissions and the calculation can therefore be made on the input side of the extended economic efficiency analysis, i.e. parallel to cost accounting.

Chapter 4
Digital Twin Artefact (Implementation)

This chapter presents the development and functionality of the tool (artefact) for configuring and evaluating production systems using the example of the small batch production of scooters in Werk150, the ESB Business School's learning factory on the campus of Reutlingen University. First, this chapter outlines the logic and functioning of the artefact and describes the set-up of the experiments for data collection. In addition, the data and its collection, for example with the help of suitable sensors, will be discussed.

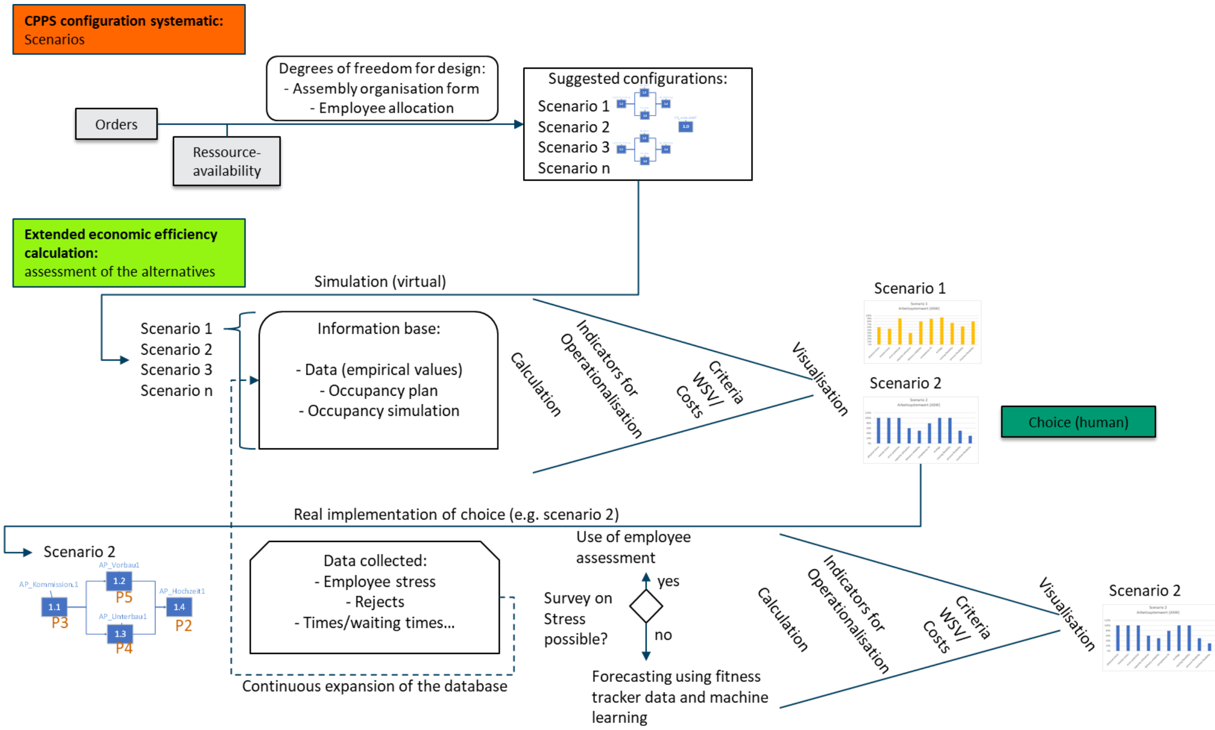


Figure 65: Model of the developed artefact of the configuration and evaluation systematics

4.1 Data collection in scooter production at the Werk150 for the determination of a reference model for an intelligent production system

Since the aim of the simulation is to forecast all data that are necessary for a holistic assessment with the help of the EEA extended by the work system value, the currently missing information must be provided as a supplement. For the development and implementation of the assessment systematic, the first data for the information base are collected. These are preliminary data that will be permanently expanded by surveys and data collections in order to secure the statistical significance in the long term. For the collection of data (empirical values), various scenarios were carried out at the Werk150.

4.1.1 Design of experiment

The simulation tool that provides the information to enable the calculation of the partial costs and the work system value is based on a simulation of the occupancy planning. In order to be able to consider not only general information on the orders, the resources and the results of the occupancy planning, but also the information not yet included regarding the employee load and the error potential in the evaluation of possible scenarios, experiments were carried out in the Werk150, which should provide data with the help of which the simulation tool can be expanded.

In experimental design, there are 3 basic ways to structure experiments (Dr. Hans-Joachim Graf 2019). Full factorial experimental designs cover every possible combination, which enables many precise findings, but is associated with a great deal of effort and is therefore unusual in scientific practice. The second option is the one factor method, where one optimises one factor at a time. Although this approach sounds plausible, it often produces false results in reality. The last option is the statistical design of experiments, in which one proceeds according to the grid principle and in this way creates a mathematical model by testing the influencing factors at different levels. This is the most elegant and most common way, but it only works for continuous influencing factors.

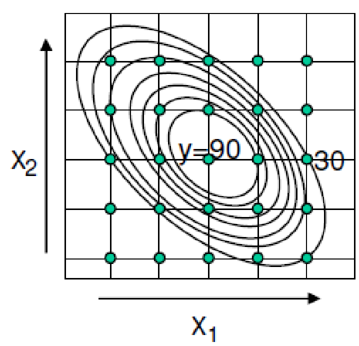
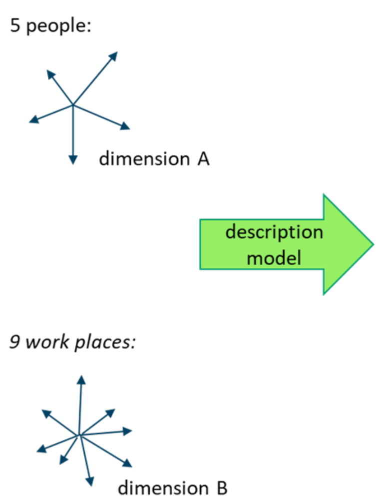


Figure 66: Design of experiments for continuous influence variables x1 and x2 (Adam) (Dr. Hans-Joachim Graf 2019)

Since the influencing factors: people and workplaces are categories that cannot be continuously subdivided into levels, but are described mathematically as vectors in different dimensions, the choice of the experimental design fell on the full factorial design, in which all possible combinations are tested directly.



Ø Measured values

Person	Work place	Stress mental 1(high) – 5 (low)	Stress physical 1(high) – 5 (low)	Reject rate
P1	T1_orderpick.	3	3	0,166
P1	T1_base	2	2	0,166
P1	T1_stem	4	3	0,2
P1	T1_IWP	3	4	0,25
P2	T1_orderpick.	4	5	0,166
P2	T1_base	5	1	0,23
P2	T1_wedding	1	3	0,2
…	…	…	…	…

Figure 67: Selection of the full factorial design for the collection of empirical values for the description model

The aim of the first tests is to collect data for a large number of variants in order to be able to develop the simulation tool. The focus in the first stage was on pragmatically obtaining reference values for the missing information in order to be able to implement the assessment logic. For this purpose, 2 basic production alternatives were built for each of the two scooter types Flex Blue (FB, type 1) and Beewatec Silver (BS, type 2). These are described in the concept as basic scenarios. Line production for scooter assembly for the Flex Blue (FB) is divided into 4 workplaces and for the Beewatec Silver (BS) into 3 workplaces. On the other hand, single-workstation assembly was carried out for both scooter types, in which all work steps are performed by one employee at one workplace. In addition to the choice of the basic scenario, different allocation options for the employees provide a degree of freedom for the design of scenarios. The possible allocation options result from the qualification of the employees, which are shown in the following qualification matrix. This contains information about which workplaces can be carried out by which people. A cross symbolises that the workplace can be filled by the employee. With the help of the experiments, all possible combinations of employee and workplace were tested. P1-P5 symbolise the employees. The employees with a green background are available for the current allocation.

Table 26: Qualification matrix of the experiments in the Werk150 for data collection

	P1	P2	P3	P4	P5
FB_order picking		x	x	x	x
FB_assembly base	x	x	x		x
FB_assembly stem	x	x		x	x
FB_wedding	x	x	x		x
FB_individual wp	x	x	x	x	x
BS_assembly base	x		x	x	x
BS_assembly stem	x		x	x	x
BS_wedding	x		x	x	x
BS_individual wp	x	x			

The following tables show the scenarios of the conducted assembly experiments to collect initial data for the development of the architecture of the reference model for work system assessment based on the digital twins. The experiments were made possible by the support of fellow students from the Digital Industrial Management and Engineering course and took place at Werk150, the learning factory at Reutlingen University. In order to achieve the greatest possible variability in employee assignments, representative shifts with a duration of 45 minutes were carried out in the experiments. The only exception is the single workstation for the Beewatec Silver (BS) with a shift duration of more than 70 minutes, as at least one complete scooter was to be produced. The shifts run during the test in different scenarios are listed below.

Table 27: Day 1 of Assembly Experiments at Werk150

Work Place (WP)	Shift 1	Shift 2	Shift 3	Shift 4
FB_Order Pickung	Person 2	Person 1	Person 4	Person 3
FB_Assembly Strem	Person 4	Person 5	Person 3	Person 2
FB_Assembly Base	Person 3	Person 4	Person 1	Person 5
FB_Wedding, Quality, Packaging	Person 1	Person 3	Person 2	Person 4

FB_Disassembly	*Person 6*	*Person 6*	*Person 5*	*Person 1*

Table 28: Day 2 of Assembly Experiments at Werk150

Work Place (WP)	Shift 1	Shift 2	Shift 3	Shift 4
FB_Individual WP	Person 3	Person 5	Person 2	Person 1
BS_Assembly Strem	Person 1	Person 3	Person 5	Person 2
BS_Assembly Base	Person 2	Person 1	Person 3	Person 4
BS_Wedding, Quality, Packaging	Person 5	Person 2	Person 1	Person 3

Table 29: Day 3 of Assembly Experiments at Werk150

Work Place (WP)	Shift 1	Shift 2
BS_Individual WP	Person 5	Person 4

Table 30: Approximate number of rollers produced per shift

Basic scenario	Scooter per 45min
FB Line	8
FB EP	2-3
BS Line	2-3
BS EP	0-1

Data collection

After each shift, the times per component are measured for the respective employee and workstation combination and each component is marked as OK or not OK at the end of the work step, which makes it possible to derive a statement about the reject rate of the employees at the respective workstations. If a product is classified as not OK, it leaves the production line and no rework is planned. The quantitative recording of the reject rate is critical due to the small number of rollers produced and is mainly aimed at determining assumed values for model development. The simplest and at the same time most meaningful indicator of employee stress is a survey. During the assembly tests, the employees were asked about their subjective perception of their physical and mental stress and asked to rate it on an ordinal scale from 1 (unpleasant) to 5 (pleasant). Unlike the error rate, employee stress is independent of the number of units.

Name: Producttyp: FlexBlue Date:
Semester: Age: Height: Weigth:

Workplace:

Piece	Start (*time*)	End (*time*)	Ok (no reject)	Not ok (reject)
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Personal perception/ assessment:

Physical stress

Mental stress

General stress

Note (optional):

Figure 68: Blank form for data collection from one shift (one employee at one workstation) on times, rejects and stress survey

The literature shows that some body-reactions are meaningful indicators of the stress level and the individual perception of stress. Data on body reactions bring an additional value especially if the employees cannot or may not be interviewed and the production scenario actually implemented is to be assessed. The body reactions should be as meaningful and measurable as possible. During the literature research, heart rate, oxygen saturation, cortisol level and body conductivity (sweating) turned out to be meaningful and measurable. In the search for suitable sensors, the choice fell on a fitness tracker that measures the oxygen saturation in the blood (SPO2) and the heart rate (1/s) at 4-second intervals during the entire shift and saves them in a CSV file.

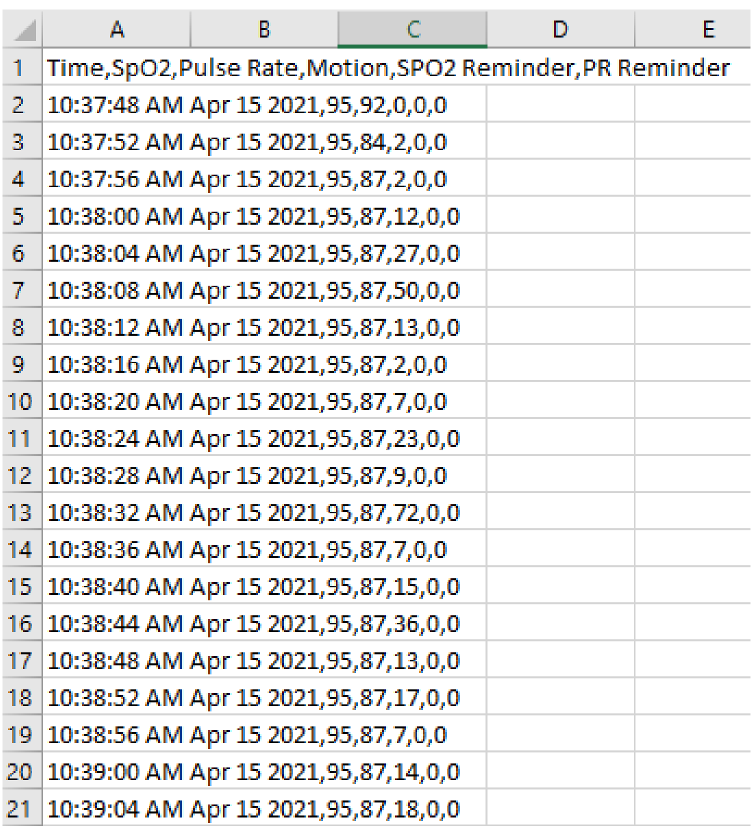
Fitness Tracker

Just like the body reactions used as indicators, fitness trackers are subject to various requirements. They should have sensors that can measure as many meaningful body reactions as possible and record, store and make the data immediately available as raw data. If this requirement is met, the price of the measuring equipment and the costs associated with its use are also considered. During the research, several fitness trackers emerged as potential options.

Fitness Tracker	Fitbit Sense	Wellue O2Ring	Garmin Forerunner 245	AppleWatch Series4
Sensors	*Skin temperature sensor,* Skin Conductance Response (SCR), *Oxygen saturation (sp02 value)* *Heart rate (ECG)*	*Oxygen saturation (sp02 value)* *Heart rate (ECG)*	*Heart rate (ECG)* *Heart rate variablility (ECG)*	*Oxygen saturation (sp02 value)* *Heart rate (ECG)*
Advantages	Many Sensors with meaningful indicators	Easy Data Transfer (CSV-File), no additional cost Abo, easy usage	no additional cost	no additional cost
Disadvantages	- *Export as CSV (max. 1month after test and only with an premium abo)* - *No recording during the day* - *API does not allows to export the raw data*	Only 2 indicators	Only 2 indicators (both based on heart rate) Data Transfer only possible with additional coding in Python	Only 2 indicators Unclear how/ if an Raw Data Transfer Export is possible
Price	250€ + 80€/year	170€	250€	250€

Figure 69: Selection of a fitness tracker as sensors for body reaction measurement during the assembly experiments

After consideration, the decision was made in favour of the Wallue O2Ring, which measures the heart rate and oxygen saturation in the blood at intervals of 4 seconds. Especially the CSV format and the easy data transfer as well as the price were decisive for the choice. The following charts show the raw data recorded.

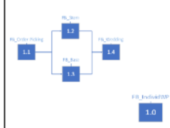
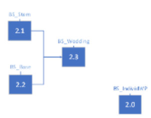


	A	B	C	D	E
1	Time,SpO2,Pulse Rate,Motion,SPO2 Reminder,PR Reminder				
2	10:37:48 AM Apr 15 2021,95,92,0,0,0				
3	10:37:52 AM Apr 15 2021,95,84,2,0,0				
4	10:37:56 AM Apr 15 2021,95,87,2,0,0				
5	10:38:00 AM Apr 15 2021,95,87,12,0,0				
6	10:38:04 AM Apr 15 2021,95,87,27,0,0				
7	10:38:08 AM Apr 15 2021,95,87,50,0,0				
8	10:38:12 AM Apr 15 2021,95,87,13,0,0				
9	10:38:16 AM Apr 15 2021,95,87,2,0,0				
10	10:38:20 AM Apr 15 2021,95,87,7,0,0				
11	10:38:24 AM Apr 15 2021,95,87,23,0,0				
12	10:38:28 AM Apr 15 2021,95,87,9,0,0				
13	10:38:32 AM Apr 15 2021,95,87,72,0,0				
14	10:38:36 AM Apr 15 2021,95,87,7,0,0				
15	10:38:40 AM Apr 15 2021,95,87,15,0,0				
16	10:38:44 AM Apr 15 2021,95,87,36,0,0				
17	10:38:48 AM Apr 15 2021,95,87,13,0,0				
18	10:38:52 AM Apr 15 2021,95,87,17,0,0				
19	10:38:56 AM Apr 15 2021,95,87,7,0,0				
20	10:39:00 AM Apr 15 2021,95,87,14,0,0				
21	10:39:04 AM Apr 15 2021,95,87,18,0,0				

Figure 70: Raw data in CSV format (left) and visualisation (right) of the fitness trackers

4.1.2 Data processing and information model

For each combination of employee and workplace, the times per component and the waiting times were recorded and saved in a summary CSV-/ Excel file. The recorded average times per workplace are shown in the next table. These collected times verify the work schedule times and serve as a basis for the discrete-time occupancy schedule simulation.

(Assembly) organisations-form / Product type	Line				Individual Workplace				
FlexBlue (FB) (Werk150) 	**Machine/ WP**	**Times/pcs in min (work plan line)**	**Ø -Times/ pcs in min (experiment)**	**Activities (Work plan)**	**Machine/ WP**	**Times/pcs in min (work plan line)**	**Times in min (work plan line +25% *)**	**Ø -Times/ pcs in min (experiment)**	**Activities (Work plan)**
	FB_Order Picking (1.1)	4,05	4,78720	380-490	FB_Individ WP (1.0)	18,14 (4,54)	21,78 (5,45)	19,52 (4,88)	350-370; 400-490; 590-760; 770-900; 920-1000; 1060-1110; 1130-1140
	FB_Stem (1.2)	4,84	6,92321	770-900					
	FB_Base (1.3)	4,73	4,82312	350-370; 590-760					
	FB_Wedding (1.4)	4,52	5,20402	920-1000; 1060-1110; 1130-1140					
Beewatec Silver (BS) (Werk150) 	**Machine/ WP**	**Times/pcs in min (work plan line)**	**Ø -Times/ pcs in min (experiment)**	**Activities (Work plan)**	**Machine/ WP**	**Times/pcs in min (work plan line)**	**Times in min (work plan line +25% *)**	**Ø -Times/ pcs in min (experiment)**	**Activities (Work plan)**
	BS_Stem (2.1)	36,32	36,7875	220-370	BS_Indivi dWP (2.0)	98,12	122,65	112,12	220-710
	BS_Base (2.2)	30,96	36,1416	380-490					
	BS_Wedding(2.3)	30,84	39,1541	500-710					

* [Lotter; Wiendahl 2006]

Figure 71: Working times of the work schedules and average values of the experiments

The body reactions, SPO2 level and pulse rate measured during the experiments are stored by the fitness trackers in the form of the CSV file presented earlier, which records the values at a time interval of 4 seconds. However, some situations can occur during data collection that make it difficult to process and thus compare the collected data. The fitness trackers are set up in such a way that they record the data from the moment the test person puts the sensor on the finger. When the tracker is removed from the finger again, a 10-second countdown begins, at the end of which a CSV file is saved. During the experiments, it can happen that the measurement is inadvertently interrupted for a short time, for example when a participant washes his hands for hygienic reasons during the break. Likewise, there is the case that several shifts are saved in a single CSV file. In order to be able to compare the maximum, minimum and average pulse rate and the minimum and average oxygen saturation for the same time periods for all test persons and also to clean the data from outliers, a code for evaluating the CSV files was programmed with the help of Pandas. The programme code is attached in the appendix. The sample result for the first shift of person 1 (P1) in the 2nd experiment in the Werk150 is shown in the next figure.

```
-----------------------------------------------------
index from 0 to 675
             SpO2  Pulsfrequenz    Bewegung  SpO2 Reminder  PR Reminder
count  671.000000    671.000000  671.000000          671.0        671.0
mean    94.849478     92.701937   34.777943            0.0          0.0
std      0.520902     10.457047   32.773304            0.0          0.0
min     93.000000     71.000000    0.000000            0.0          0.0
25%     95.000000     87.000000   12.000000            0.0          0.0
50%     95.000000     92.000000   25.000000            0.0          0.0
75%     95.000000    102.000000   45.000000            0.0          0.0
max     96.000000    113.000000  148.000000            0.0          0.0
-----------------------------------------------------
```

Figure 72: Analysis of the fitness tracker raw data using Pandas (Python) for the first shift (45 min) of experiment 2 of person 1 (P1).

Data storage and management

A summary CSV file was created for data storage and management. This forms a central information basis for the later calculation of the criteria and complements general order and resource information and information from the occupancy simulation. In the table, each row represents a shift of a workplace with an assigned employee. Likewise, the associated data collected using Wallue O2Ring, oxygen saturation and pulse rate, have been summarised and stored in the data-managing CSV file. In addition to the minimum and average oxygen saturation, the minimum, maximum and average heart rate is recorded for the entire shift. In addition, the documented scrap rates and the subjectively perceived mental, physical and general stresses surveyed after the shift were included for the shifts. The next illustration shows an excerpt of the data.

Table 31: Excerpt from the status of the CSV files for data management after the first experiment at Werk150

Person	workplace	av_spo2	min_spo2	av_heartrate	min_heartrate	max_heartrate	rejects	mental_stress	physical_stress	general_stress
P1	FB_assembly stem	95	93	96	75	120	0	3	4	4
P1	FB_assembly base	95	93	93	80	113	0.125	3	4	4
P1	FB_wedding	95	92	101	85	122	0.1666666667	5	5	5
P1	FB_individual wp	96	94	102	85	120	0.3333333333	2	4	3
P1	BS_assembly stem	95	92	91	75	105	1	1	4	3
P1	BS_assembly base	96	94	93	85	112	0	1	4	3
P1	BS_wedding	96	93	91	75	102	0	3	5	4
P1	BS_individual wp	95	92	86	72	100	0	2	4	3
P2	FB_order picking	96	92	77	63	99	0	2	2	3
P2	FB_assembly stem	96	92	79	62	92	0	3	3	4
P2	FB_assembly base	96	93	75	60	90	0.2	2	3	3
P2	FB_wedding	96	93	75	52	91	0.2	4	4	3
P2	FB_individual wp	96	94	87	68	105	0	3	3	3

Procedures for the processing and using of the collected data

The measurement data collected in the Werk150 serves to close the gap in the necessary information base for calculating the work system value criteria of mental and physical employee stress, as well as error potential. In the following, two possible procedures are presented in order to be able to obtain predictive estimates for future shifts with the help of the expected values.

Case A): Post-hoc approach

If there are already empirical values from previous experiments for future planned combinations of workplaces and employee allocation, the average data on the surveyed stress and error rate can serve as an estimate/indication of the results of future scenarios. Since the concept for configuring the scenarios limits the allocation of employees to workplaces for which they are already qualified, experience values are already available for all possible employee and workplace combinations, which can preferably be used directly for the evaluation. Average experience values thus serve as a reference for future shifts. The experience values of mental stress, physical stress and committee are summarised in the following tables.

Table 32: Experience matrix: Mental stress

Mental stress					
workplace	P1	P2	P3	P4	P5
FB_order picking		2	5	4	5
FB_assembly base	3	2	2		4
FB_assembly stem	3	3		3	2
FB_wedding	5	4	4		4
FB_individual wp	2	3	3	4	5
BS_assembly base	1		4	2	5
BS_assembly stem	1		3	4	3
BS_wedding	3		5	2	3
BS_individual wp	2	1			

Table 33: Experience matrix: Physical stress

Physical stress					
workplace	P1	P2	P3	P4	P5
FB_order picking		2	3	3	5
FB_assembly base	4	3	4		4
FB_assembly stem	4	3		4	1
FB_wedding	5	4	5		2
FB_individual wp	4	3	4	2	5
BS_assembly base	4		5	4	5
BS_assembly stem	5		5	3	4
BS_wedding	5		5	3	4
BS_individual wp	4	3			

Table 34: Experience matrix: Reject rate

Physical stress					
workplace	P1	P2	P3	P4	P5
FB_order picking		2	3	3	5
FB_assembly base	4	3	4		4
FB_assembly stem	4	3		4	1
FB_wedding	5	4	5		2
FB_individual wp	4	3	4	2	5
BS_assembly base	4		5	4	5
BS_assembly stem	5		5	3	4
BS_wedding	5		5	3	4
BS_individual wp	4	3			

Case B) Machine learning approach:

The prediction of the subjective assessment of load (stress) for combinations of workplace and employee can be done without the use of direct empirical values for the combination with the help of machine learning algorithms.

```
# load the data from file
data = pd.read_csv('DatenWerk150.csv', delimiter=';')

# define the target
regression = False
target_value = 'general_stress'
dataY = data[target_value]
dataX = data.drop(columns=['general_stress', 'mental_stress', 'physical_stress', 'rejects'])
```

Figure 73: Definition of the initial features and target parameters

```
# define kNN clasifier
neigh = KNeighborsClassifier(n_neighbors=3)
neigh.fit(X_train, y_train)
y_pred_knn = neigh.predict(X_test)
print("Number of mislabeled points out of a total %d points (KNN): %d" % (X_test.shape[0], (y_test != y_pred_knn).sum()))

clf = GaussianNB()
clf.fit(X_train, y_train)
y_pred_gnb = clf.predict(X_test)
print("Number of mislabeled points out of a total %d points (GNB): %d" % (X_test.shape[0], (y_test != y_pred_gnb).sum()))

mlp = MLPClassifier(max_iter=30000, hidden_layer_sizes=(100, 100), random_state=42)
mlp.fit(X_train, y_train)
y_pred_mlp = mlp.predict(X_test)
print("Number of mislabeled points out of a total %d points (MLP): %d" % (X_test.shape[0], (y_test != y_pred_mlp).sum()))
```

Figure 74: Train-test analysis for machine learning approaches (KNN, GNB, MLP) based on collected data

The code allows to import the CSV file for data management described above and can make predictions using the data. In the example shown, the general stress level is predicted using the information about the workplace, the employee, and the columns with the collected fitness tracker data. For continuous target values such as the error rate, regression analyses (ridge regression, linear regression) are available in the model, but it is also possible to apply other algorithms such as k nearest neighbour (KNN), Gaussian naïve bias (GNB) or a classification using Multi-Layer Perceptron (MLP), which makes sense for categorical features. For the surveyed stress with values on the integer scale of 1-5, both methods can be applied. While the capabilities of machine learning algorithms are very powerful and offer the potential to make predictions for employee-workplace combinations for which no data has yet been collected, the use of the fitness trackers is not a good idea. The use of fitness tracker data is expected to improve the quality of predictions. The problem, however, is that predictions using an algorithm can only be as good as the labelled data with which it is taught, and the prediction result cannot therefore be better than the target values against which it is compared. Therefore, by default, it makes more sense to take the empirical values directly.

Summary of the determination of expected values

The machine learning approach has the potential to use fitness trackers to determine employee engagement and thus avoid some human bias in the survey. However, since the machine learning algorithms are taught using the employee engagement results and are also measured by a match to them, they can only be as good as they are. Therefore, it makes sense to preferably use the unbiased mean values of the employee survey directly. However, the machine learning approach has application potentials in case a staff survey might not be possible for some reason. For these reasons, it was decided to use the post-hoc approach to calculate the stress and the error potential in the calculation system.

Learning approch for continous data collection

For both approaches presented, it is advantageous for the validity of the evaluation results if they are based on a good database of empirical values. Since the data base collected in the context of this research work is still small in order to make accurate predictions, the acquisition of sufficient experience values is basically a critical aspect for ensuring the predictive ability. Therefore, the learning approach for continuous data collection was used to design a framework for permanent data collection in the form of an information feedback from the real factory into the description model, which serves as part of the information basis for the calculation of the work system value criteria stress and error potential. It is hoped that this process approach will improve the forecasting ability of the system over time.

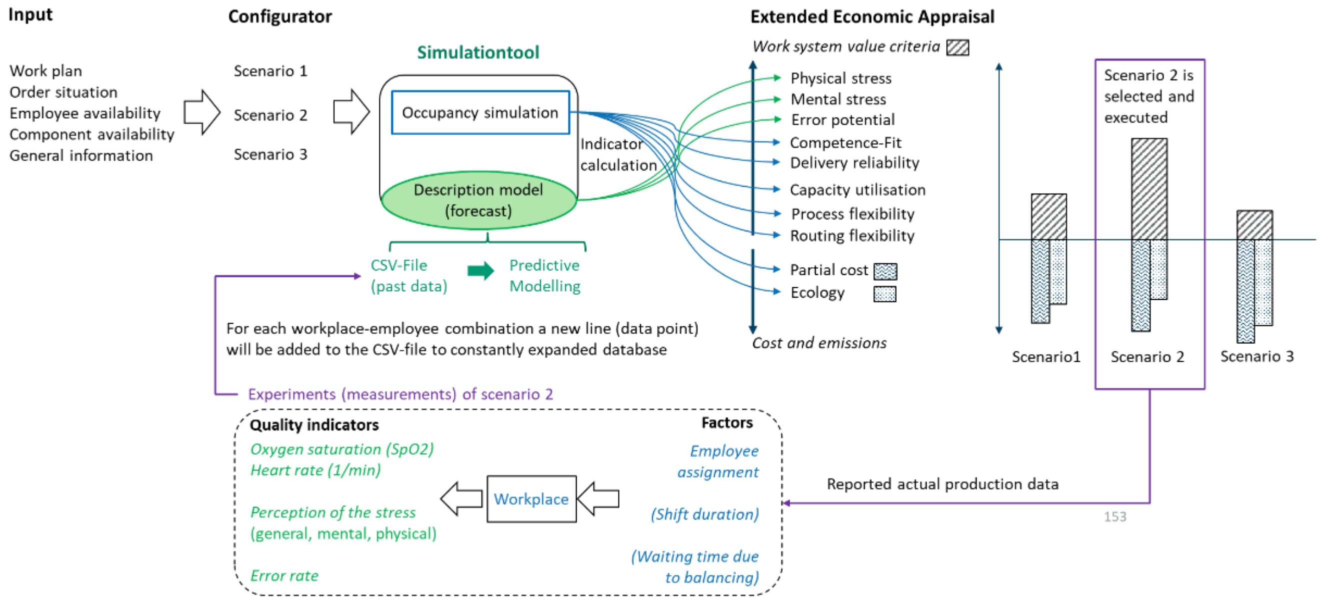


Figure 75: Learning approach for continuous data collection

4.2 Simulation and data management

The following sketch is intended to provide a simplified overview of the technical implementation and information flow of the occupancy planning simulation within the scope of this research work. In brief, a CSV file with order-related information is created and an input vector is generated from it, which is sent to the simulation programme on the servers of Reutlingen University via VPN. After running the simulation, the results are returned with the help of an output vector from which an export file is generated that can be used to access the results.

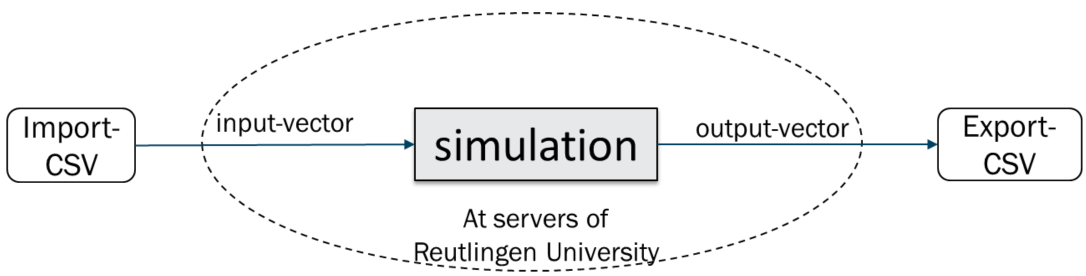


Figure 76: Technical implementation of data import, simulation, data

4.2.1 Data import

Creation of orders and generation of a CSV file for the simulation import

- Routing variant (basic scenarios: option A, B, C, D, ...)
  - Checking component availability
  - Checking personal availability using the skills matrix
- Number of orders per product type
- Delivery date

For the occupancy simulation of the scenarios, some information must be provided. An input in the form of a CSV file was chosen, which is read in Python (PyCharm). In the following, the information provided is shown using the example of a line assembly for an order of 60 BeewatecSilver and 12 FlexBlue. In addition to information on the operating calendar (incl. exception days) and weekly time models, other planning settings such as the occupancy logic (e.g. Line Fill), prioritisation or performance level of the resources can be selected. Orders and order-related information can also be specified, such as order completion status, required material and planned start and end times. The following tables show additional relevant information on the orders and pre-arrangement relationships, which are also included in the import for the simulation.

Table 35: Occupancy planning incl. precedence relationships for line productions (FlexBlue and BeewatecSilver)

Order identifier	Working aisle identifier	predecessor	successors	workplace
00815|01	00815|01|1		00815|01|2, 00815|01|3	FB_Line|FB_L1|001
00815|01	00815|01|2	00815|01|1	00815|01|4	FB_Line|FB_L2|002
00815|01	00815|01|3	00815|01|1	00815|01|4	FB_Line|FB_L3|003
00815|01	00815|01|4	00815|01|3		FB_Line|FB_L4|004
00817|01	00817|01|1		00817|01|3	BS_Line|BS_L1|006
00817|01	00817|01|2	00817|01|1	00817|01|3	BS_Line|BS_L2|007
00817|01	00817|01|3	00817|01|2		BS_Line|BS_L3|008

In addition to the workstation times (processing times of machines) and personnel times per piece, the input also includes the ordered number of machines per product type and the degree of overlap, which indicates whether the machines can work in parallel.

Table 36: Workplace information for line productions (FlexBlue and BeewatecSilver)

workplace	Already started (Y or N)	Planned quantity	Processing time [min]	Personnel time [min]	Overlap percentage [%]
FB_Line|FB_L1|001	N	60	4,05	4,05	100
FB_Line|FB_L2|002	N	60	4,73	4,73	100
FB_Line|FB_L3|003	N	60	4,84	4,84	100
FB_Line|FB_L4|004	N	60	4,52	4,52	100
BS_Line|BS_L1|006	N	12	30,96	30,96	100
BS_Line|BS_L2|007	N	12	36,32	36,32	100
BS_Line|BS_L3|008	N	12	30,84	30,84	100

For the operations of the line workstations a complete overlap is chosen, i.e. as soon as piece 1 is transferred from the first line workstation to the second workstation, the employee at workstation 2 starts assembling piece 1 and the employee at line workstation 1 starts with piece 2. Since the production in the Werk150 has a make to order characteristic and is only produced to order, the order quantities per product type are part of the output information.

4.2.2 Simulation

Discrete-time simulation using the manufacturing execution system (FLS) (occupancy simulation tool).

- Simulation takes information from CSV import:
    - Routing variants incl. machine times (verified standard times)
    - Priority relationships of the routing variants
    - Order quantities
- Occupancy simulation is carried out

To enable access to the functions of the simulation software, a scheduling application programming interface (API) is used. For this purpose, an import vector for the simulation is created from the CSV file (or Excel file) with the input data.

```
from simulation import api
path = 'C:\\input (L_L).xlsx'

#new instance of the scheduling API
SchedulingApi = api.SchedulingApi()
#first of all an Excel must be loaded
SchedulingApi.load_import_vector(n_path=path)
```

The simulation software is only accessible at the virtual desktop at the Reutlingen University. Therefore, in order to run the simulation, the program is provided with connection data, to connect with servers of Reutlingen University. For this step to be working, a virtual private network (VPN) connection to the university servers has to be established first.

```
#Connection data to the scheduling server
SchedulingApi.endPoint = "http://134.103.24.81:28000"
```

In Python, possible processing strategies and wait time modes are read. In addition, the default strategy and default waiting time type are set. Finally, the simulation is carried out using the generated input vector.

```
#Run the simulation (returns a dataframe (result) and information (info))
result, info = SchedulingApi.do_simulation \
    (n_inputvector=input_vector, n_strategy=default_strategy, n_wait_time_mode=default_wait_time)
result.to_excel("output(L_L).xlsx")
```

4.2.3 Data export

Simulation generates a CSV file (Pandas Data Frame).

- Information from the simulation:
    - Times per workplace
    - Delivery reliability
    - Capacity utilisation

- Basis for scenario design by allocating employees with the help of the qualification matrix
    - Option A.1, A.2, B.1, C.1, C.2, C.3, ...

After the simulation, an export vector is provided. With this, the simulation results are delivered and output as a data frame. The simulation results contain start and end times for each workplace. Information on the earliest and latest start and end times is also provided. Information on waiting times and the delay of the task is also included. In addition, it is noted whether the task was carried out as planned. In a direct occupancy simulation in the production control system, it is also possible to calculate the delivery reliability and capacity utilisation. The following table shows an excerpt of the data frame exported to Excel for display reasons, which contains the simulation results.

	TaskItemId	MainResourceId	Start	Stop
0	00815|01|1	FB_Line|FB_L1|001	2021-12-14T14:17:52.722	2021-12-15T09:56:34.722
1	00815|01|2	FB_Line|FB_L2|002	2021-12-14T14:17:52.722	2021-12-15T10:33:17.922
2	00815|01|3	FB_Line|FB_L3|003	2021-12-14T14:17:52.722	2021-12-15T10:39:14.322
3	00815|01|4	FB_Line|FB_L4|004	2021-12-14T14:36:31.602	2021-12-15T10:40:36.402
4	00817|01|1	BS_Line|BS_L1|006	2021-12-14T14:17:52.722	2021-12-15T11:52:14.622
5	00817|01|2	BS_Line|BS_L2|007	2021-12-14T14:17:52.722	2021-12-15T12:50:07.722
6	00817|01|3	BS_Line|BS_L3|008	2021-12-14T15:18:43.422	2021-12-15T12:51:47.022

Figure 77: Simulated times per workplace using the example of the basic scenario (L_L)

The data frame resulting from the simulation is an information pillar of the subsequent calculation. The calculation was also implemented as a Python programme, which facilitates data transfer.

4.3 Calculation implementation

In order to understand the implementation of the extended economic efficiency calculation, the calculation is placed in the overall context of the assessment systematic in the following.

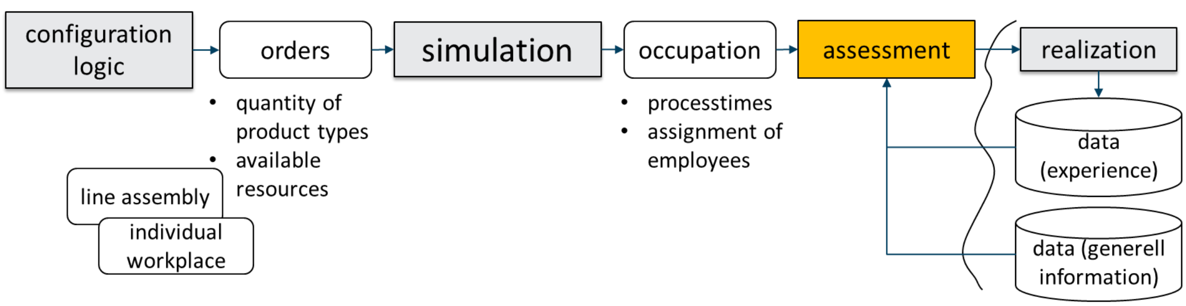


Figure 78: Implementation and information flow of the rating systematic

4.3.1 Information basis and weighting aspect for the criteria calculation

As described in the concept, different information is needed to calculate the individual criteria. Some criteria can already be calculated from the choice of the basic scenario and information on the resources and their availability. Other criteria require additional information on the occupancy times from the simulation and still others require further information on staff allocation and empirical values from past assembly experiments. The criteria corresponding to the information needed for the calculation are summarised below.

- Calculation of the following criteria using the basic scenarios
    - Routing flexibility
    - Process flexibility
    - Machine flexibility (changeover)
- Calculation of the following criteria using additional information from the simulation
    - Ecology (machine times, power consumption per machine)
    - Delivery reliability
    - Capacity utilisation
    - Partial costs
- Calculation of the following criteria with the help of additional information from employee allocation
    - Competence fit
    - Mental stress
    - Physical stress
    - Error potential/ rejects

The concept has also already addressed the fact that when calculating some of the criteria for the overall scenario, individual assessments related to the employee, the workplace or the ordered product types must be aggregated with each other. The weighting of the criteria is weighted according to time or value added.

- Without weighting
    - Partial costs (including the machine flexibility indicator changeover cost)
    - Ecology (C02 emissions)
- Weighting of the following criteria using the simulated process times
    - Mental strain
    - Physical demands
    - Competence fit: competence delta (preference fit: the individual wishes of the employees)
- Weighting of the following criteria with the help of value added
    - Error potential
    - Competence fit: competence delta (the match between job requirements and employee profile)
    - Flexibility corridors (process, routing flexibility)
    - Delivery reliability

4.3.2 Implementation of the calculation logic

The presented solution shows an implementation of the calculation formulas developed in the conceptual part of this thesis.

Mental and physical stress

```python
def avg_stress(stress_levels, workplace, worktime, person_scheduling):
    total_time = 0
    stress_time = 0

    for place, time, person in zip(workplace, worktime, person_scheduling):
        # if there is no value for the stress level -> skip this data point
        if stress_levels[place-1][person-1] == -1:
            continue
        total_time += time
        stress_time += time*stress_levels[place-1][person-1]
    total_stress = stress_time/total_time
    return total_stress

```

Figure 79: Implementation of the physical and mental stress criterion in python

The input parameters for this function are the stress levels (for mental or physical stress) obtained from the assembly experiments and stored in a matrix (experience matrix: mental stress, physical stress), and the workplace, working time and person scheduling, which are lists corresponding to the columns of the export data frame from the simulation. The function presented iterates sequentially and simultaneously through the workplace, the working time and the person planning and sums up the working times at the workplace and the stress level of the person working at that workplace times the duration. (to weight the individual stress with the duration) A missing value in the stress_level matrix is indicated by the value -1 and skipped when accessed. The -1 in the indexing of the stress_levels matrix is due to the fact that indexing in Python for lists and matrices starts at 0, so that the stress level of person 1 at workplace 1 is stored under stress_levels [0][0].

Error potential

```python
def error_potential(rejection_rate, workplace, person_scheduling, va_order):
    total_value_added = 0
    total_error_potential = 0

    for place, va, person in zip(workplace, va_order, person_scheduling):
        # if there is no value for the error potential -> skip this data point
        if rejection_rate[place-1][person-1] == -1:
            continue
        total_value_added += va
        total_error_potential += va*rejection_rate[place-1][person-1]

    return total_error_potential/total_value_added

```

Figure 80: Implementation of the error potential criterion in python

The input parameter to this function are the rejection_rate, which is a table, like the ones for stress, obtained from the experiments. Additional information is derived from the workplace and person_scheduling which are lists that correspond to the employee occupancy. To enable the weighting of the individual reject rates, which are indicators for the error potential, the va_order is used, which is the value added per workplace as explained earlier. As in the stress level criterion the function consecutively sums up the added value and the product of rejection rate and value added. The missing values in the rejection rate are also omitted. The returned value then is again the division of both sums according to the criterion's formula.

Competence fit (preference and competence delta)

```
def preference(preference_levels, workplace, worktime, person_scheduling):
    total_time = 0
    preference_time = 0

    for place, time, person in zip(workplace, worktime, person_scheduling):
        # if there is no value for the stress level -> skip this data point
        if preference_levels[place-1][person-1] == -1:
            continue
        total_time += time
        preference_time += time*preference_levels[place-1][person-1]
    total_preference = preference_time/total_time
    return total_preference

```

Figure 81: Implementation of the preference which is one part of the preference fit

The Implementation of the preference is analogous to the stress criteria, but instead of the stress levels, there are preference levels for persons on workplaces.

```
1  def competence(competence_ce, competence_cr, person_scheduling, va):
2      competence_delta = 0
3      total_va = 0
4      for i, ct in enumerate(competence_ce):
5          for j, ce in enumerate(ct):
6              if ce == -1 or competence_cr[i][person_scheduling[j] - 1] == -1:
7                  continue
8              competence_delta += abs(ce - competence_cr[i][person_scheduling[j] - 1]) * va[person_scheduling[j] - 1]
9      total_va += sum([va[x - 1] for x in person_scheduling])
10     m = len(competence_ce)
11     return competence_delta/(m*total_va)
12
13
```

Figure 82: Competence delta which is the second part of the competence fit

The inputs are competence_ce, which is a two-dimensional matrix and shows the self-estimation of each person regarding the fulfilment of each competence type on an ordinal scale from 1-5 and competence_cr which is a matrix as well, which shows the requirement profile of each workplace (expert estimation). More inputs are person_scheduling as before and the value added (va). This function iterates over the rows (outer for loop) and the columns (inner for loop) and sums up the absolute difference between the competence estimate and the competence requirement times the value added. The competence_cr and va values are accessed according to the person_scheduling. In this implementation the sum of the values added isn't calculated iteratively as before, this is because this function does not iterate over the va values as before. The sumation is done with the inbuild function „sum "instead, the right va values are picked with a list comprehension according to the persons_scheduling, as shown in line 9 of the figure above. The final value then is obtained by dividing the sumed up competence deltas by m times the sum of the va values. The criterion of competence fit is simply calculated as the middle value of preference and competence delta.

Delivery reliability

```
def delivery_reliability(va, orders, td):
    reliability = 0
    value = 0
    for o, v, t in zip(orders, va, td):
        if o == 0:
            continue
        value += o*v
        reliability += o*v*t
    return reliability/value

```

Figure 83: Implementation of the delivery reliability criterion

The inputs are va, as before, orders, which is the ordered amount of the product types respectively and td is a list which denoted if a product was delivered in time, this is explained later. The value added per product type is calculated by the va value times the orders of this product. This function iterates over the orders, va and td and sums the products according to the criteria formula.

For the calculation of the td values, first the delay for each product has to be calculated, this is done as follows:

```
def delay(dataframe, goal_time):
    fb_stop_line = dataframe.loc[dataframe['MainResourceId'] == 'FB_Line|FB_L4|004']['Stop'].values[0]
    bs_stop_line = dataframe.loc[dataframe['MainResourceId'] == 'BS_Line|BS_L3|008']['Stop'].values[0]
    fb_stop_individual = dataframe.loc[dataframe['MainResourceId'] == 'FB_IndWP|FB_IndWP|005']['Stop'].values[0]
    bs_stop_individual = dataframe.loc[dataframe['MainResourceId'] == 'BS_IndWP|BS_IndWP|009']['Stop'].values[0]

    fb_stop_time_line = to_timestamp(fb_stop_line)
    bs_stop_time_line = to_timestamp(bs_stop_line)
    fb_stop_time_individual = to_timestamp(fb_stop_individual)
    bs_stop_time_individual = to_timestamp(bs_stop_individual)

    fb_delay_line = fb_stop_time_line - goal_time[0]
    bs_delay_line = bs_stop_time_line - goal_time[1]
    fb_delay_individual = fb_stop_time_individual - goal_time[2]
    bs_delay_individual = bs_stop_time_individual - goal_time[3]

    return fb_delay_line.total_seconds() / 60, bs_delay_line.total_seconds() / 60,
           fb_delay_individual.total_seconds() / 60, bs_delay_individual.total_seconds() / 60

```

Figure 84: Calculation of the td (delay information)

This function calculates the delay for each product on the production line and on the individual workplaces. The input is a Pandas data frame which contains the output data from the simulation and the goal times when the production should be completed. The times when the workplaces are finished are extracted from the data frame, then the time difference in minutes is calculated for each product, a positive value means that the product is delayed, a negative value means that the product was finished in time. From the delay the td values from before can now be calculated.

```
td = [0 if x > 0 else 1 for x in delay(dataframe, goal_times)]

```

Figure 85: With this list comprehension the td value of a product is set to 0 if it is delayed and to 1 otherwise.

Process- and routing flexibility

```
def process_flexibility(pa, va):
    return sum([a*v for a, v in zip(pa, va)])/sum(va)
```

Figure 86: Implementation of process and routing flexibility

The routing flexibility and the process flexibility are calculated analogous to each other, both sum the product of the va values times the ap or ar values, as described in chapter 3, and then divide this sum be the sum of the va values. For both criteria this calculation is done with a list comprehension and the python 'sum' function.

Machine flexibility (changeover effort)

```
def changeover(setup_time, wage, person):
    cost = 0
    for i, time in enumerate(setup_time):
        cost += (time/60)*wage[person[i] - 1]
    return cost

```

Figure 87: Implementation of change over (as indicator for machine flexibility)

The changeover function calculates the total cost for changing from one product type to another by summing up the setup time for each workplace times the wage for the person who does the changeover on this workplace.

Ecology (CO_2 emissions)

```
def total_co2(time, machine, machine_energy, co2perkWh):
    co2 = 0
    for t, m in zip(time, machine):
        co2 += (t/60)*machine_energy[m-1]*co2perkWh
    return co2

```

Figure 88: Implementation of CO_2 emissions as indicator for ecology criterion

This implementation calculates the total CO_2 emission for the ecology criterion by iterating over the machines and the time they were running. The emission per machine is calculated by multiplying the runtime with the energy consumption and the CO_2 emission per kWh. The emissions are then summed up and returned.

Exemplary calculation result

Below is an example of the result of the simulation of an order with 60 Flex Blue and 12 Beewatec Silver rollers, which is to be delivered by 2pm the next day.

Table 37: Employee allocation for example scenario (S) 0

Scenario (S)	Workplace (WP)	S0
FB Line	FB_order picking	P2
	FB_assembly base	P1
	FB_assembly stem	P4
	FB_wedding	P3
FB Individual WP	FB_individual wp	
BS Linie	BS_assembly base	P3
	BS_assembly stem	P4
	BS_wedding	P5
BS Individual WP	BS_individual wp	

The result provides the criteria metal stress, physical stress, error potential, competence fit (consisting of competence delta and preference), delivery reliability, routing flexibility and process flexibility in %. The changeover cost (as an indicator for machine flexibility), the total costs and the CO2 emissions are provided in absolute figures. As described earlier, the criterion of capacity utilization was identified relevant and defined as one of the work system value criteria. The used simulation program provides a simulation of the capacity which can usually be directly used as output. However, in the special circumstances, using the simulation program on the VPN of the Reutlingen University, an additional application programming interface (API) was necessary, which was built with the support of the software provider. Unfortunately, no data export for the calculation tool could be achieved for the information on capacity utilisation so far. Therefore, the aspect of capacity utilisation in the work system value is not included until the problem is solved

```
mental stress in %: 67.37526572464675
physical stress in %: 77.53628198809848
error potential in %: 77.62083333333334
competence fit in %:  73.75529128745409
delivery reliability in %:  50.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  1308.0092533333334
total co2:  13.5949
work system value in %:  69.7077627143142
```

Figure 89: Result for example scenario S0

As the value added for the FlexBlue is assumed to be 12€ and for the Beewatec Silver 60€, the total value added of the scenario is the same for both product types. Since the order for the FlexBlue is finished on time, but the Beewatec Silver is delayed, this results in a delivery reliability of 50%. The changeover cost was calculated in this example as 58,33€. The preference has taken the value of 62,7% and the competence delta 84,7%, which together, equally weighted to each other, form the work system value criterion competence fit. If all work system value criteria are equally weighted, a value of 69,7% is calculated for the example

Both the staff assignment, the basic scenario, the resource availability and other information can be adapted in the system and thus enable the configuration of different scenarios with different characteristics.

Chapter 5
Validation and Verification

In this chapter, I try to validate and verify the gain in knowledge of this study and its implications for the domain of research in the field of EEA based production planning. The challenge in validating the developed systematic is that it relates to a newly developed design artefact. "Design science research, by definition, changes the state-of-the-world through the introduction of novel artefacts" (Vaishnavi et al 2019). It is "most effective when alternating between pragmatic and critical realist perspectives" (Bunge 1984). Since the research work includes different professional areas and is thus based on multi-paradigms for gaining and ensuring scientific knowledge, two variants are combined for the methodological procedure for validating and verifying the results:

Table 38: Methodology for the validation and verification (overview)

1) Performance measures of the design artefact (technology demonstration)	2) Expert Opinion (Face Validation) (and comparison with existing concepts)

1) On the one hand, the application potential of the developed system of the created artefact in the environment of the Werk150 including a check of the general validity for longer shift durations is considered. In addition, the generalisability and applicability of the system for other production systems is examined by transferring it to another industrial system.

2) On the other hand, a verification of the developed the assessment systematic and the technical implementation is carried out with the help of expert feedback.

5.1 Design artefact performance measures (demonstrator)

In this chapter, the results of the design artefact are discussed, the procedure of the experimental data collection is discussed and the collection process is reflected. Post-hoc and machine learning based approaches are covered. Furthermore, additional experiments in the Werk150 with longer shift durations than the initial experiments for model creation are addressed. Finally, the transferability of the system is demonstrated using the example of a small-series wine bottling plant.

5.1.1 Validation of the systematic and its elements with data collected from the Werk150

Below are the calculation results for 12 different scenarios, which were calculated automatically by the calculation tool using the developed logic, mainly using the results of a simulation based on verified work plans, and post-hoc values as estimated values for future shifts. For the two different product types FlexBlue (FB) and BeewatecSilver (BS) in Werk150, each of which can be assembled in a line or at a single workstation, there are a total of four possible combinations of basic scenarios. For each of these 4 combinations of basic scenarios, 3 different employee allocations were chosen. This results in a total of 12 example scenarios, which are shown in the following table.

Table 39: Employee allocation for the example scenarios S1-12

		FB Line & BS Line			FB Line & BS Ind. WP			FB Ind. WP & BS Line			FB Ind. WP & BS Ind. WP		
Scenario (S)	Workplace (WP)	S 1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
FB Line	FB_order picking	P2	P4	P5	P2	P4	P5						
	FB_assembly base	P1	P3	P3	P5	P3	P3						
	FB_assembly stem	P4	P5	P2	P4	P5	P4						
	FB_wedding	P5	P1	P1	P3	P2	P1						
FB Individual WP	FB_individual wp							P4	P1	P2	P4	P1	P2
BS Linie	BS_assembly base	P1	P3	P5				P1	P3	P5			
	BS_assembly stem	P2	P4	P3				P2	P4	P3			
	BS_wedding	P3	P5	P1				P3	P5	P1			
BS Individual WP	BS_individual wp				P1	P1	P2				P1	P2	P1

The results of the partial costs, the carbon dioxide emissions and the work system value, with equally weighted criteria, are summarised below for each scenario S1-S12 and visualised in the following graph.

Table 40: Results of the example scenarios S1-12

Scenario (S)	S 1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Partial cost [€]	1305	1356	1405	2678	2684	2673	2274	2555	2593	3625	3883	3883
CO_2 emission [kg]	13,6	13,6	13,6	26,4	26,4	26,4	27,7	27,7	27,7	40,5	40,5	40,5
Work system value [%]	76,1	75,5	83,9	67,8	67,5	57,1	68,3	66,2	71,5	62,2	49,2	61,5

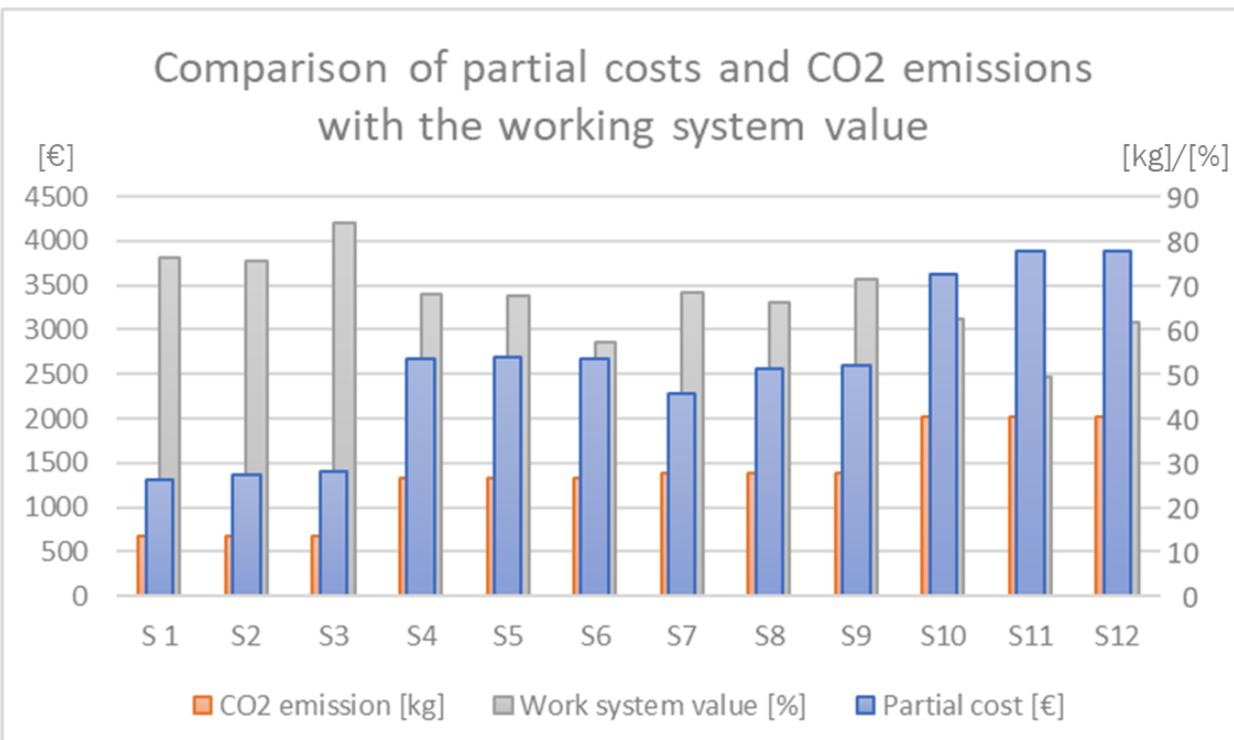


Figure 90: Visualisation of the results of the example scenarios S1-12

Tendencies of the results

The presentation of costs, emissions and work system value is already an aggregated form of information. This can be an advantage for decision making, but information is also lost when searching for insights. In order to discuss the results, the individual results of the work system value criteria are considered in addition to the aggregated results. These can be found in the appendix for the example scenarios S1-S12. In general, the visualisation of the results shows that the choice of the basic scenario has a strong influence on the result, especially on the costs and emissions. It can also be seen that the work system value is less dependent on the basic scenario, but changes with the allocation of employees.

Individual workplaces tend to have longer delivery times, which leads to poorer delivery reliability when delivery deadlines are tight. In the example simulation, an order was started on the afternoon of 25 January, where the orders for 60 FB and 12 BS were to be delivered on 27 January at 12 o'clock. Individual workplaces have higher costs due to longer working hours, more expensive workplaces due to the availability of all tools at one workplace and in the example, higher employee costs were also assumed for the better qualified employees who can also work at individual workplaces. As a result of the longer overall occupation of the workplace, the energy consumption and the emissions are also increasing for the individual workplace. Probably the best scenarios are Scenario 1 and Scenario 3, with low costs and emissions at a high work system value.

Review of the functionalities of system elements

The data situation in connection with the experiments for the development of the design artefact is referred to in detail. However, this is only one of several aspects that should be discussed at this point. Besides the data, which were additionally collected experimentally in order to develop a complementary description model, the simulation results play an important role for the calculation. To verify the quality of the discrete-time simulation, the times were recorded for all experiments. These coincided with the already verified work plan times and were validated for the simulation. Apart from the information, the coherence of the evaluation logic is crucial, especially for the work system value criteria. The validation of the evaluation logic cannot be simply confirmed with the help of collected data, but the reasonableness was derived by the literature research approach described in detail and discussed several times in intensive discussions of a research group consisting of two students and two professors of Reutlingen University. The iterative process with regular feedback from experts and subsequent implementation of suggestions for improvement already ensured the validity of the developed evaluation logic during the development process, which was finally implemented in the form of formulas. For this purpose, but above all to ensure the system architecture from a technical point of view and its implementation, a verification meeting was also held with a professor from the field of business informatics and business analytics, which is discussed in Section 5.2.

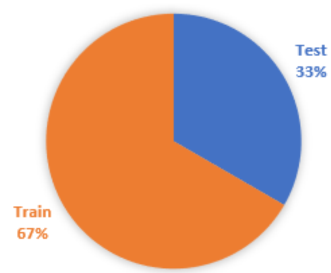
Reflections on experiential data (Statistics and Data Science)

As explained earlier, after careful consideration, a full factorial design approach was chosen to set up the experiments. A general qualitative survey on interests and competences was conducted, which can be found in the appendix, and a qualitative survey on stress was conducted after each shift. During the experiments, the rejects and times were recorded quantitatively. The full factorial design of experiment and limited samples only allow for tendencies to be identified at this stage. Therefore, the current problem for the significance is that due to the small number of measurement points, it is only preliminary data, which must be considered when predicting future scenarios and assessing the results of the investigation to gain knowledge. The problem of insufficient data is to be solved over time with the help of a learning approach for continuous improvement of the description model, which extends the prediction of the simulation & permanent use of established statistical validation methods of data science for quality assurance, such as accuracy, precision, recall (sensitivity).

In order to work out and provide the principle procedure for the statistical data control in advance, the procedure was applied to the first data capture in the Werk150, consisting of 36 data points. The performance of the prediction can ideally be statistically validated by using established validation methods in data science, such as accuracy, precision, recall (sensitivity), which is achieved with the help of a train-test split by comparing the predicted values of the test portion and the real values of the test portion. Although the statistics are not reliable due to limited data, the principle procedure is to be developed using a train (2/3) - test (1/3) split. Despite the limited data, the additional use of fitness tracker data for prediction shows better performance than without the fitness tracker data.

Person	workplace	av_spo2	min_spo2	av_heartrate	min_heartrate	max_heartrate	rejects	mental_stress	physical_stress	general_stress
P1	FB_assembly stem	95	93	96	75	120	0	3	4	4
P1	FB_assembly base	95	93	93	80	113	0.125	3	4	4
P1	FB_wedding	95	92	101	85	122	0.166666666666667	5	5	5
P1	FB_individual wp	96	94	102	85	120	0.333333333333333	2	4	3

Figure 91: Extract from the data set of the first experiments at Werk150




```
linear regression average error: 0.8392029867094628
ridge regression average error: 0.7833992171495928
```

```
Number of mislabeled points out of a total 12 points (KNN): 7
Number of mislabeled points out of a total 12 points (GNB): 6
Number of mislabeled points out of a total 12 points (MLP): 9
kNN average error: 0.8333333333333334
GNB average error: 0.6666666666666666
MLP average error: 1.0
Gaussian naive bayes:
Test values:  [3, 1, 4, 4, 3, 4, 4, 3, 3, 5, 4, 5]
Predictions:  [3, 3, 4, 5, 4, 5, 3, 3, 5, 5, 4, 5]
```

Figure 92: Example of a train-test comparison of actual to predicted values using the example of general stress

For the example of general stress, the train test was conducted using different modelling techniques. Since the teaching is based on the integer responses of the survey, both categorical and continuous techniques are acceptable. In the example, the continuous techniques linear and ridge regression, as well as the categorical techniques, k nearest neighbour (KNN), Gaussian naive Bayes (GNB) and a multilayer perceptron (MLP) were applied. The relatively inaccurate result of the MLP can be attributed to the fact that this technique tends to overfit, especially for small data sets. For the current state of the data, the GNB performed best with an average error of 0.67, which still leads to quite inaccurate values on a scale of 1-5. At the end of the graph on the train test result, the 12 test data points of the total 36 data points are shown. On the one hand the predicted values and on the other hand the real measured values are shown, which allows a comparison between prediction and actual and an estimation of the precision. It is also evident that 6 of 12 data points for the GNB were incorrectly labelled, i.e. predicted, which corresponds to an accuracy of 0.5. In summary, it can be stated that the analysis of the current data has shown that a prediction using machine learning does not bring the desired success. Therefore, the assumption is confirmed that it makes more sense to directly use the collected post-hoc mean values for stress (and error potential) as assumption values. In order to constantly improve the data situation and thus also the quality of the forecasts, a continuous learning approach is pursued, as already described.

In addition to the problem of the small number of data points collected, the error potential criterion, which is calculated by the reject rate, has the hurdle that for each 45-minute shift that was run in the first experiment, there is the problem of insufficient sample size. In order to estimate the plausibility of the values as well as a basic tendency of the distribution of the rejects, the distribution of all persons was visualised for all line workplaces and shifts respectively. This observation explicitly does not serve to examine the significance of the mean values of the individual workers at the respective workplaces.

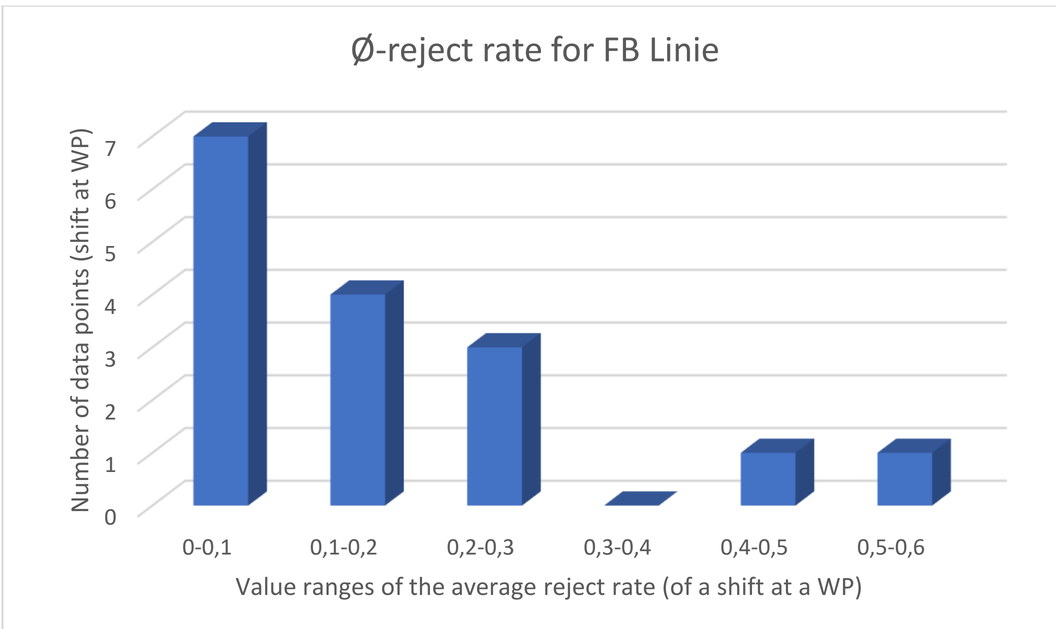


Figure 93: Average reject rate per work places for the line assembly shifts

5.1.2 Additional experiments for validation in the Werk150

Since it is ultimately a matter of being able to draw generally valid conclusions from the data collected, considerations of inductive statistics, also called inferential statistics or inferential statistics, are necessary. The aim of our study is ultimately to be able to draw conclusions about the best production alternative. On the one hand, the question arises whether the employees can already make a meaningful assessment of the stress at the workplaces after 45 minutes. On the other hand, the manageable number of rollers produced per workstation in 45 minutes raises the problem that the determination of the values for the reject rate is not very precise. To check the validity of the 45 min shift and to additionally validate the developed configuration and rating system including simulation, a further test was carried out in the Werk150. Five consecutive 45-minute shifts were carried out with a break of 3 minutes each, which corresponds to a 4-hour shift. For the 4h shift, for example, 42 rollers are produced per line workstation as planned for the FlexBlue roller, which allows a more accurate statement about the reject rate of the people at the respective workstations. The more frequently the rollers are drawn or the more rollers are

produced, the more accurate the statement about the distribution of the rejects and thus about the reject rate. When using mean values, the rule of thumb of 30 trials applies in order to be able to represent a standard normal distribution, which, however, is not practically feasible for all scenarios with 30 shifts. Therefore, an approach is chosen in which selected scenarios are statistically meaningfully investigated in order to validate the procedure in principle. The implementation of selected scenarios as a 4h shift indicates that the results show high similarities with the values of the 45min shift or do not change much after the 45min.
In summary, it can be said that the implementation of a 4h shift (5x45min) with constant employee deployment indicates that conclusions, e.g. on employee stress, can already be drawn after a shift duration of 45min over the entire shift duration and do not change significantly over time. The collected values of the first experiment can therefore allow tendencies for conclusions to be drawn for longer shifts, which is necessary for a practical application. The 4h shifts show slight tendencies of a typical daily pattern in the stress perception, which could be considered in the model. The 4h shift allows, albeit only for one distributional variant, a larger sample size for rejection.

5.1.3 Transferability of the system (wine bottling)

In this section I show the transferability of the rating system to a production process of a small enterprise. Additionally, the application of the concept to a real small batch production serves to collect an extensive sample which ensures statistical certainty. To reflect the knowledge gained from the scooter production at the Werk150, I have investigated a wine bottling process of a wine maker from the Reutlingen region. Due to its manageable complexity and batch size, the process was suitable to validate the applicability of the rating system. In addition, the example has significance for Reutlingen and Stellenbosch, as both cities are located in winegrowing regions. Transferring the system to this use case includes applying the different elements of the rating system, which are the configuration and simulation of scenarios and using collected data to compliment the simulation results for a predictive assessment of the scenario performance, which is measured by short term costs and the work system value, which represents a selection of indicators for soft factors. The process from empty bottle to stored wine bottle is described below. The specific work steps derived from this are subsequently explained.

Figure 94: Empty bottles

The empty bottles are first rinsed in pairs upside down at a sulphur station with sulphurous acid suspension in order to sterilize them. To remove as much suspension as possible from the bottle before filling, the bottles are dried upside down on a bottle tree for a few minutes. This step is shown on the following photo.

Figure 95: Draining of sulfur after sulfurization

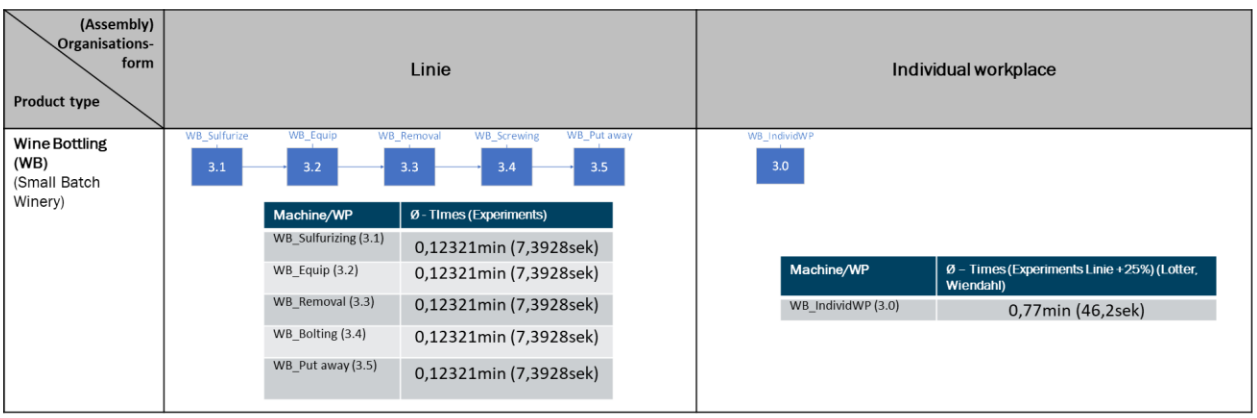
Now the sterile and dry bottles can be placed on the rotating filling system. To do this, the filling nozzle is inserted into the bottle and the bottle is set down. Once the bottle is completely filled, an employee checks the fill level, removes the bottle and positions a cap on each bottle.

Figure 96: Bottling plant

On a screwing machine, the cap is placed on the thread of the bottle. The bottle is now completely filled and is stored until its serving or delivery.

Figure 97: Wine bottle storage

The wine bottles are standardly filled in line at 5 successive workstations. An individual workstation variant, which fulfills the same task, was considered for the study, as well. The line production is divided into five workplaces following one another in a linear sequence. At the first workplace, the empty and clean wine bottles are sprayed out and thus disinfected with the aid of sulphur and stored temporarily for drying. In the next step, a filling machine is loaded with the sulfurized bottles, which are then filled automatically. At the third place, the full bottles are removed from the filling machine, inspected for quality and fitted with a cap. In the next step, the cap is attached to the bottle by using a screwing system. The bottle is then ready to be served and can be stored in the wine rack in the final work step. The summary of the work steps for line production and the individual workplace are shown below. The times shown for the line workstations are average values that are used as standard times for the simulation.



Machine/WP	Ø - Times (Experiments)
WB_Sulfurizing (3.1)	0,12321min (7,3928sek)
WB_Equip (3.2)	0,12321min (7,3928sek)
WB_Removal (3.3)	0,12321min (7,3928sek)
WB_Bolting (3.4)	0,12321min (7,3928sek)
WB_Put away (3.5)	0,12321min (7,3928sek)

Machine/WP	Ø – Times (Experiments Linie +25%) (Lotter, Wiendahl)
WB_IndividWP (3.0)	0,77min (46,2sek)

Figure 98: Activity sequencing and times of Line assembly and individual WP Assembly for the wine bottling process

The basic scenario of line assembly was carried out in the experiment with a fixed allocation of employees. Accordingly, the qualification matrix allows only one specific workplace for each employee, which limits the configuration options. For each combination of employee and workplace, an employee survey was conducted on subjective stress after each shift and stress measured using fitness trackers. An example of the data collected from the 2 shifts performed is shown for one individual below. The counter sums up the measuring points that are collected every 3 seconds. So, the first shift with 1161 counters corresponds to 58 minutes and the second work shift with 4541 counters corresponds to 227 minutes, which is similar to the 45minutes and 4h shifts of the experiments in the Werk150.

```
----------------------- shift 1 ------------------------------
P1 (Manuel) - Kopie
               SpO2  Pulse Rate       Motion  SPO2 Reminder  PR Reminder
count  1161.000000 1161.000000  1161.000000         1161.0       1161.0
mean     95.161068   87.810508    48.559001            0.0          0.0
std       2.729924   11.630160    37.114550            0.0          0.0
min      88.000000   57.000000     0.000000            0.0          0.0
25%      93.000000   79.000000    19.000000            0.0          0.0
50%      96.000000   89.000000    40.000000            0.0          0.0
75%      98.000000   98.000000    71.000000            0.0          0.0
max      99.000000  114.000000   148.000000            0.0          0.0
----------------------- shift 2 ------------------------------
P1 (Manuel) - Kopie
               SpO2  Pulse Rate       Motion  SPO2 Reminder  PR Reminder
count  4541.000000 4541.000000  4541.000000         4541.0       4541.0
mean     94.881524   80.460251    29.545915            0.0          0.0
std       2.179311    9.385785    33.545037            0.0          0.0
min      89.000000   55.000000     0.000000            0.0          0.0
25%      94.000000   74.000000     1.000000            0.0          0.0
50%      96.000000   80.000000    19.000000            0.0          0.0
75%      96.000000   85.000000    45.000000            0.0          0.0
max      99.000000  113.000000   148.000000            0.0          0.0
```

Figure 99:Example of the merged fitness tracker data per shift for one employee

With the help of fitness trackers, which were worn on the finger of the participants during the shift, the oxygen saturation and pulse rate were recorded and saved as a CSV file. Since the stored CSV data was partially interrupted and therefore a comparison of average values during the shift or minimum and maximum values was not possible, I wrote some lines in Python to combine all data of an employee from one shift to one CSV file. The code can be found in the appendix.

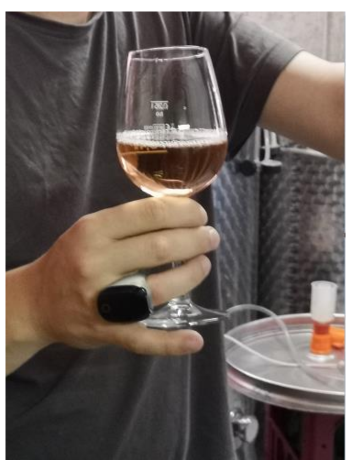


Figure 100: Measurement of oxygen saturation and pulse rate using fitness trackers

In this assembly test, a total of 2500 wine bottles were prepared, filled, screwed and stored in an assembly process. The total rejects were in this case was one bottle. The developed rating logic, which is

implemented in Python, performs a holistic system rating based on data from the simulation and additional post-hoc empirical data or fitness tracker data and machine learning. I fed the collected data from employees, as well as the work schedules, into Python so that the different alterative scenarios could be simulated.
The following two figures show the detailed calculation results of the rating system for the line assembly and the single workstation variants for an order of 2500 wine bottles.

```
mental stress in %: 92.0
physical stress in %: 80.0
error potential in %: 99.96000000000001
competence fit in %:  76.05882846882577
delivery reliability in %:  100.0
routing flexibility in %:  20.0
process flexibility in %:  0
total costs [€] (including changeover):  723.8
total co2 [kg]:  0.616
work system value in %:  66.85983263840367
```

Figure 101: Result of the rating system for the line assembly of wine bottling (2500 bottles)

```
mental stress in %: 80.0
physical stress in %: 60.0
error potential in %: 100
competence fit in %:  81.18372265611083
delivery reliability in %:  100.0
routing flexibility in %:  0
process flexibility in %:  0
total costs [€] (including changeover):  2598.75
total co2 [kg]:  3.35
work system value in %:  60.16910323658726
```

Figure 102: Result of the rating system for single workstation of wine bottling (2500 bottles)

The mental and physical stress was determined for both scenarios using the post-hoc approach. The potential for error is about 100% for both variants, which corresponds to the optimal value, although the formulation can be misleading. The reason for this is that desirable values reach a high percentage, so aggregating the work system value makes sense. The competence fit is 50% the match of the workplace requirement with the employee profile and 50% the individual preference of the employee for a workplace. In the case of the line assembly scenario, the values of all 5 employees are considered. For the delivery reliability, the delivery date was assumed to be one week, which both scenarios fulfil. However, the delivery time for the single workstation takes 4days and for the line only about 5h. Routing Flexibility and Process Flexibility perform weakly in both cases, since the workstations are usually only available once and only one defined activity per workstation is possible at the winery. The final value of the aggregated work system value with equal weighting of the criteria is 66% for the line and 60% for the individual workstation, which is in favour of the line scenario. The comparison of the cost side is very interesting. Since there is no fully developed option for individual workstation filling, the bottling equipment must be permanently in operation in this case as well, which entails rental costs on the one hand and increased electricity and thus emissions on the other. In this case, the machine runs permanently under normal power consumption and does not fall into a creep current mode. The same applies to the upstream filter plates and the capping machine for the bottles. The example shows that wine bottling in the case study does not make sense at a individual workstation except in special situations, such as employee shortage, because both work system value, costs and emissions rate poorly.

5.2 Expert interviews to verify the results

This section is devoted to evaluating feedback from industrial engineering experts on the concept of this study and its technical implementation in the form of a design artefact. The goal of the conducted interviews is to provide qualitative verification of the research findings. The method chosen for the interviews is a structural content analysis according to Mayring (Mayring and Gläser-Zikuda 2008; Mayring 2010) in which the recorded and transcribed expert answers are assigned to inductively formed categories. After the formation of categories for the answers of all experts to the first two questions (about 30% of the material), an inter-rater reliability test was performed with the support of my fellow student, whose thesis topic is related to that of my final thesis. The coefficient of Cohens Kappa was calculated to be 0.58 (P0 =0.341 and Pe=0.591) which indicated an modertate to substantial agreement.

With the help of the categories, the answers could be summarized in terms of content and discussed more easily. A qualitative investigation in the form of expert interviews is particularly informative with regard to the practical relevance of the derived criteria, the logic of the calculation formulas and the system architecture of the rating system. The data was already collected during the research at Reutlingen University. The duration of the interview sessions is about 1 - 1.5 hours in total. Before the semi-structured interview, there is already an exchange via e-mail, so that the experts have the opportunity to read up on the thesis and the associated scientific paper in advance. During the interview, about half an hour is spent summarizing the topic and answering questions and ambiguities. The pure interview time is therefore on average about 45 minutes. The experts are asked open-ended questions that serve as a guide for the interview.

Table 41: Participants of the expert interviews

Organisation	Position	Academic Grade	ID	Interview Duration*
Reutlingen University	Professor of business informatics and business analytics	Prof. Dr.	ID1	53min
International Industrial Consult IIC AG	Consultant in industrial engineering, political science and economics	Dr.rer.pol	ID2	41min
International Industrial Consult IIC AG	Consultant and senior project manager	Dipl.-Ing.	ID3	44min
Université du Luxembourg	Professor of engineering science	Univ.-Prof. Dr.-Ing.	ID4	67min
MTM-Organisation; TU Wien	Professor of industrial engineering	Univ.-Prof. Dipl.-Ing. Dr. techn.	ID5	32min
Audi AG	Work scientist and Industrial engineer	Dr.-Ing.	ID6	46min

*refers to the duration of the interview from the first question of the guidance document

The experts' answers were be recorded during the interview, provided the interviewees agree to this, in order to be able to reflect on and transcribe the conversations in detail afterwards. In addition, notes are documented. The guiding questions asked and the analysis of the answers are listed and discussed below.

Questionnaire and the analysis of the answers:

Basic comments at the beginning after the presentation of the topic and concept:

ID2 and ID3 noted at the beginning that they would focus on the basic work design and not on comparing the short-term scenarios. They said that work design was a prerequisite for all scenarios. Ergonomic workstations and medical care were given as examples. Since ID2 said that high employee stress was the standard these days, he suspected that the criterion would provide little contrast in a comparison. ID4 and ID6 questioned the role of humans in the decision-making process and consider an automated selection of the best scenario to be useful by also combining work system value, costs and emissions to avoid a possible human bias by the decision maker and to objectify the result. In this context, ID4 also considers a direct monetary evaluation of work system criteria such as flexibility, employee workload, CO2 emissions, etc. to be possible, which would allow aggregation in monetary units. Likewise, a preselection based on input size would be useful. E.g., at 5 or 500 pieces, a different workstation variant would be recommended. ID4 found the result visualization of cost, work system value and emission confusing due to the direction of the bars.

Is the chosen approach to deriving the work system value criteria and the associated calculation reasonable? (Qualitative selection of relevant text sources, quantitative word analysis, qualitative analysis with the help of literature and expert assessment).

The experts consider the approach of a multi-stage derivation of the rating criteria to be reasonable. ID1 believes that the derivation approach depends on the problem. Common fully automated approaches that search databases for defined terms and examine texts quantitatively with analysis software to prepare the qualitative assessment would have the advantage that human bias is avoided and large amounts of data can be examined efficiently. However, humans are still better able to process text for content, he said. ID1 and ID2 point out the importance of the definition of terms and see this only partially secured and possible too short-sighted in the chosen approach, which analyses word frequency. Furthermore, the question arose whether the derivation approach sufficiently captures the relevance of the criteria for the system (ID4) and the individual requirements of the employee (ID3). ID4 suspects that similarly good results could be achieved with less effort using expert systems. From ID5's point of view, a 2-step approach would also suffice, in which either the first step of qualitative text and term selection or the final step of qualitative literature analysis is dispensed with. ID6 considers the approach to be an appropriate means.

Does the assessment logic developed help to make more comprehensive decisions and thus improve work systems?

In principle, all the experts consider a widening of the dimensions in the assessment of the scenarios to be useful. However, ID4 questions whether there would actually be users for the assessment within the company and whether extended information preparation, apart from an advantage for the image among the shareholders, brings added value or only makes obvious things clear. ID2 and ID3 consider it fundamentally sensible and the right approach that both the human and the machine are considered in the work system. ID5 considers the criteria to be comprehensive and thinks that they help to make better decisions. Also, for ID6 a combination of different aspects is relevant and ID1 is convinced that it is essential to take into account the employee and his stress more carefully, because happy employees are the most productive ones in the long run. However, ID6 and ID1 point out that the chosen observation horizon is short and that aspects of process planning such as set-up costs or costs for developments (ID6) or actual consequences of employee stress such as health problems or loss of employees (ID1) may not be taken into account. They therefore suggest broadening the horizon of consideration. ID1 suggests that excessive employee strain is more likely to cause problems with mental work and less with workers in the production, and may even be beneficial to the company in the short term. In the long term, he sees flow, i.e. neither overstraining nor understraining, as the best level of stress. ID2, on the other hand, also sees a risk of falsification due to subjectivity when focusing on people. ID4 considers it possible that out of 10 criteria some could be irrelevant and falsify the result if they are weighted incorrectly. Since he would like to see a single overall result value instead of separate analysis of work system value, costs, and emissions, he considers the aggregation problem to be scientifically exciting. ID6 asked the same question for the aggregation of emissions.

Does the chosen approach to configuring and simulating the assembly scenarios make sense?

- **Selection of the basic scenario (assembly organisation form: single workstation or line)**
- **Simulation**
- **Allocation of employees**

ID1, ID4 and ID6 agree that the approach makes sense in theory and for the specific use case and that it is practical to create a model to describe the different alternatives, but that it might be difficult to implement in different kinds of industrial use cases. ID5 sees a necessity in the first step of the distinction between basic scenarios. ID2 and ID3 emphasize that before the step of configuration, the design of the working system must already have taken place for all basic scenarios and the design is not replaced by the configuration system. ID1 as an expert in the field of software architecture finds the basic approach useful. He thinks it makes sense to start with some first data, and then when there is enough data, to simulate it with the Digital Twin and at the end to think about how to implement it. The ability to predict it through a simulation to at least have a certain confidence interval by estimating how much it can fluctuate in reality is useful. Finally, the best scenario can be carried out and be checked whether it worked. And next time the system can price it in and do better. ID1 and ID6 are of the opinion that the chosen distinction between the forms of assembly organization does not sufficiently reflect reality. ID1 sees in the developed systematics with the help of customization the possibility of offering a consulting service with which an individual solution can be adapted for a concrete factory. He does not yet see an all-in-one solution.

Do the degrees of freedom in the design meet the requirements of industrial practice?

Experts ID1, ID2, ID4, ID5 and ID6 think that the industrial reality can only be represented in some parts by the variation possibilities of the model. ID1 and ID2 think that the model is correct for the use case, but do not see a general validity of the model and therefore "one size fits all" (ID1). ID1 considers the assembly organization forms individual workstation and line assembly to be real scenarios and thus very important. He also considers the selected procedure, in which reality is made describable with the help of a model, to be practicable, since it is impossible to represent the entire complexity. He recommends designing different variants for each individual production. He would also extend the model to logistics, supply chains and parts procurement. ID4 and ID5 see the model as too theoretical. ID5 views the planning horizon, with which the decision for or against a scenario can be made, as being neglected. ID2, ID4 and ID6 would like to see an additional mixed assembly organization form as a configuration alternative. ID2 and ID4 point out the aspect of teamwork, which is essential for ID2, especially for small companies. ID4 considers semi-autonomous group work, preferably in U-shape as a realistic extension option for the model. ID6 does not see any clear forms of quantity and type division in single workstation and line production and would also not recommend the semi-autonomous group as a mixed form. Nevertheless, he would consider the approach of starting with 3 basic scenarios and providing for further differentiations within the model over time to be a good idea.

Does an adjustment of the scenario lead to a meaningful change in the assessment? Have the corresponding correlations been plausibly identified?

ID1 and ID5 find the approach of storing experience data for the individual employees in the different scenarios exciting, but find it difficult to make an informed statement with their level of knowledge about the thesis. ID1 sees information feedback from stress, for example, as an interesting way to use the amount of data to improve the forecasting model and thus the assessment. ID6 also thinks the approach is very charming but limits applications to researchers, as he has privacy concerns about collecting employee-related information. As an occupational scientist, he warns about possible translation misunderstandings of stress and strain from German into English and considers the chosen DIN standards as a useful definition. He recommends the use of established tools such as the Nordic Questionaire and considers the combined assessment of mental and physical strain using the NASA Taskload Index (6items) to be the best alternative to the chosen approach. ID6 regards it as successful that the ecological, economic and social sustainability as well as demographic aspects are also adjusted in the rating by changing the scenario. He sees the correlations between scenario and rating as well fulfilled for the criteria error, competence fit, ecology, even if he critically looks at the comparison of the competence requirements per workplace and the competences per employee. He feels that the binary evaluation for the flexibility corridors is simplified but sufficient and that the delivery reliability and utilization are also okay. ID4 would refrain from developing new calculation formulas and rely on literature in the respective fields such as medicine for workload assessment. ID2 and ID3 are of the opinion that depending on the case, only 3 criteria have 90% importance in the assessment. They recommend therefore depending upon case an ABC analysis of the criteria.

Does the configuration and rating system help to improve production systems in a holistic way?

The experts unanimously agree that the basic concept can be helpful. ID1 considers the concept with the steps of criteria definition, an interim simulation, the calculation of criteria based on forecast values for decision support to be interesting and good and sees long-term added value particularly in the step of the final information feedback. ID4 sees the benefit especially if the concept is implemented correctly, possibly in relation to the Manufacturing Execution System. ID6 sees great potential at Audi AG for assessing soft factors that have not yet been exploited and thinks this is also relevant for long-term planning. ID5 thinks that the system can help to improve production system according to given requirements but not the requirement itself. ID2 and ID3 require the system to be user-friendly on the one hand and to be used for a meaningful area or use case on the other hand. ID2 values transparency and comprehensibility of the rating and the associated decisions for the employees as very important. It is important to communicate why employees are assigned to changing workstations, he said. A longer period for the simulation, e.g. over the duration of a week, could avoid frequent changes so that employees have more stability.

Are the approaches to assess the criteria stress and rejects useful?

- **Post-hoc (experience matrix)**
- **Machine learning (using fitness tracker data)**

The experts consider the approaches to be interesting and a tried and tested means. ID6, ID2 and ID3 consider both approaches to be suitable and see the use of machine learning as a sensible way of reacting to empirical values as well as to pulses and oxygen saturation. ID4 considers both options to be possible, especially for determining the probability of error (rejects), but points out that statistically meaningful data is a prerequisite, which plays a special role for the machine learning alternative. For personal data, he sees a union issue. For ID1 both the post-hoc and the machine learning alternative hold advantages and the choice depends on the question. Post-hoc experience values are not measured live during the process and therefore a subjective falsification, because stress is sometimes perceived differently than it actually occurs. Nevertheless, most studies have shown that questionnaire-based surveys are relatively close to the actual reality. Over time, average values should be formed, which are a relatively good heuristic for the real overstress. Regarding the machine learning approach, ID4 and ID1 share the concern that random and work-independent influences distort the measurement of body responses. ID1 thinks that if the post-hoc responses are classified; the use of algorithms only makes sense if the post-hoc responses can be removed over time or if one wishes to observe the process live. Similarly, machine learning could eliminate the need to interview employees.

Is a continuous learning approach (data collection) useful to improve the significance? (The table from the first experiments was shown here.)

According to ID1 it is currently difficult to make a statement about the statistical power of the investigation and it remains with tendencies. Statements can be made about the constants that were kept the same, but of course, all the things which are varied are a conforming factor that has changed the survey method and therefore the behaviour and actually each observation starts with only one data point. Likewise, habituation and learning processes cannot be completely exhibited, even if you rotate after the shifts in the experiment. The test duration of 45 minutes, the low availability of participants and the complexity lead to a relatively difficult data collection, which would be easier in a field study in a real plant. A qualitative scientific approach would have methodical advantages, but the continuous learning approach can also improve the data over time. ID5, ID6, and ID4 perceive the continuous learning approach as a meaningful opportunity for improvement. ID4 sees it as the core of the research work. ID5 considers the loop to be meaningful only if the model is good. ID3 assumes that the validity of employee-related aspects will also improve with the amount of data. The learning approach would contribute to this. ID2 considers 2 alternatives conceivable. Either data graves are created or indications for improvements can be found, which, however, must be tested empirically.

Does the implemented system represent the developed concept? (Excel import of the orders into simulation (FLS Becos), calculation in Excel or Python).

ID1, ID2, ID3 and ID6 consider the concept to be implemented consistently. ID6 thinks the chosen implementation is plausible. ID1 considers the concept: simulate, predict, execute, give feedback to be consistent with the implementation, since the simulation is performed in PyCharm (Python) and the result is executed and then the real information returns to the last loop in Excel to intervene again where PyCharm would pull out the data again as a basis for the next simulation. This meets the continuous learning loop of the concept. The data architecture is in prototype state but the data is already converted to a processable form in Python. The system overwrites values, takes the values, changes the values, and writes the values back, which is important for permanent storage in an enterprise. ID4 thinks that a configuration logic that automatically generates scenario configurations would be relevant. For him the question is too simple, the case study too rudimentary and the tool too complex. Adjusting the weighting in the rating system when aggregating the work system value criteria is too cumbersome for him.

Are the chosen programmes and methods state of the art?

ID2, ID3 and ID4 could not make any statement about the software architecture. For ID4 the choice of the programs is also unimportant and the methodology is primarily the most important aspect. ID2 suggests ABC analysis for the choice of the types of competences for the determination of the competence-fit criterion. ID1 thinks that Python is suitable for daily business and statistical applications. For reporting purposes Excel could also be used to provide an understanding for the Board of Directors. ID5 and ID6 also think that the chosen programs are state of the art. ID6 sees the long-term maintenance of the data and the database structure as the key. In his view, Oracle Apx is an alternative to CSV files. He recommends the program Alwaysfree as an alternative for workflow-based data preparation and as a sustainable database.

Were the research objectives fulfilled and the questions answered?

According to ID1, it is clear that the formulation of the research question is very open and thus allows many variants as a solution. A clearly defined research question, from which relatively stringent hypotheses result, is preferable. The hypotheses can then be tested and one can say: it is like this or it is not like this. With the thesis presented, it depends on how the question is read. ID6 noted related to the title of the thesis that he is unsure if the model actually represents cyberphysical production systems. ID4 sees marginal advantages and a low impact in the rating system, but the scientific approach is very good in his opinion and the procedure for implementation is correct.

1) How can a CPPS be evaluated using extended economic appraisal?

If the question is to answer "how", noted ID1, the artefact comes very close to the question with a possible expression. For example, in the personnel requirements it was shown that there are other important resources where it was already agreed, and therefore it is a possible extension of the economic assessment, but the solution presented is not the only possible solution. But with the procedure the question is answered in a possible way: Assuming you know all the variables that are relevant, you can measure them somehow, and you can simulate them beforehand and then see them through, and you have a system to calculate target criteria, that's one possibility. So, the method that was developed is a possibility, and so you have answered the question. ID2 and ID3 share the opinion of ID1 that the question is very broad and it would be important to specify limits of what is feasible and what is not. They see in the developed system a necessary but also sufficient solution. From their point of view the developed solution is able to evaluate workplaces but not the whole company. For ID4 the question is answered with a hypothesis. He sees the methodology and the basic principle fulfilled, however he sees the problem as rather irrelevant.

(1.1) What are the goals of production in the Werk150?

ID1 summarizes that it is difficult to say something from outside about the exact goals of Werk150. ID4 explained that these are guidelines given by the supervisors of the thesis and employees of Werk150. The answer to this question was agreed upon in contact with employees of Werk150 and the supervisors and I additionally gained an understanding in advance of the production by preparing, planning the production experiments at Werk150 and by adding the individual workstation variant.

(1.2) How can the work system be meaningfully evaluated using a systematic approach? What information base is required for this?

For ID1 the question is answered yes for the process and also for the information basis required for the concrete implementation case, but as already said there are probably different variants to implement this, depending on the variables.

(1.3) What are the roles of the EEA and the human in the process of decision making for a scenario?

According to ID1 and ID4, a prediction is made, but the final decision belongs to the human. ID1 points out the acceptance problem with many AI applications currently and that it is important that humans still play a role in the loop. For him, this shows an expression that he would support. For ID4, the decision must lie with either man or machine. ID1 replied that the person in the loop is often important, but he is not aware of the sufficient derivation and description of this relationship in my thesis. He sees it rudimentarily answered and assumes that it is somewhere in the thesis.

2) How can a digital twin suggest design variants for the CPPS?

ID2 and ID3 again summarize that delineating the question would facilitate consideration of the question. ID4 sees the design variants limited with the help of scenarios and sees the question not only as an answerable research question, but also as a guiding question for the development of the tool.

(2.1) Who are the agents or participants of the Werk150 and what functions do they perform?

ID1 thinks that the question is already answered for the particular case of the expression. The agents were your workers, they were shifted back and forth. And since it was in the Werk150 for this use case, the question is presumably answered. ID2 sees the answer to the question in my specifications.

(2.2) What parameters and degrees of freedom are available to adjust the system?

If we stay with the use case given to you and the Werk150 and these 2 scooter types and accordingly the prediction by the Becos system (simulation software), then ID1 thinks that I have mapped the question. Adjustment parameters exist mainly through the choice of the assembly organization form and the qualification-related employee allocation. He stated that everything was stringent in the explanation and it sounded perfectly logical to him and that he would agree with that. ID3 and ID2 agree with the presented variation of the concept and see it implemented in the system.

5.3 Summary

The results of the test scenario and the discussions are favourable and proof that the conceptual model is technically feasible and that the configuration of scenarios, the simulation and the extended economic rating system was actually transformed into a working system. The implementation of the concept as a design artefact shows that the information basis for decisions can be extended to criteria, which are difficult to quantify. With the help of the design artefact, a generation of scenarios based on different order situations and the choice of the basic scenario is possible, and the simulation provides all the information necessary to calculate the estimated costs and the working system value based on the occupancy planning and empirical values. However, fundamental questions remain unanswered after the development: Is the system coherent and meaningful in itself? So, is the concept in itself purposeful and coherent? This is indicated by the literature from which the system was developed. However, additional expert opinions were necessary for assessment and validation. In addition, there is the issue of limited data, which makes it difficult to prove the general validity of the prediction. In order to check the prediction performance and the validity of the values from the 45-minute shift over a longer period of time. Firstly, a renewed assembly experiment with a shift duration of 4-hour shift was examined. Likewise, the concept was applied to the real industrial use case of a small series filling of wine bottles, which in addition to a prove of the transferability, provided larger samples.

5.3.1 Performance measures and transferability of the rating system

The functionality of the design artefact was demonstrated. Despite the use of collected data (empirical values for the staff and workplace combinations), the data base is limited and the continuous learning process will be needed to fully demonstrate the statistically meaningful predictive power. A statement about the underlying logic for the assessment and the information flows are therefore additionally verified by experts.

5.3.2 Expert assessment

The expert assessment suggests that the developed system is coherent and relevant criteria, such as employee stress, have been identified to extend the work system assessment. The system architecture and information flow including a feedback loop for continuous improvement of the database are considered useful. It was highlighted that the current information bases only allow to get tendencies but no precise forecasts. In addition, a machine learning approach would be desirable to make employee interviews obsolete in the long term.

Chapter 6
Summary, Conclusions, and Recommendations

The following chapter serves to elucidate several areas: to summarise the research work herein presented; to evaluate the knowledge gained; to point out limitations of the research work, and areas for further research.

6.1 Research summary

This study designs a possible approach for the configuration of production scenarios to fulfil orders based on the availability of resources. In order to compare possible scenarios, a set of work system value criteria was defined for an EEA, using a multi-level literature review, and a calculation logic was developed for their operation. In addition to a comparison of partial costs and emission, the work system value offers a broadening insight into different dimensions that are often not considered in production planning, such as flexibility aspects, employee stress, competence, and ecology. The assessment logic can be applied both to actual production and to a simulation of production scenarios. This helps the production planner to include aspects that are difficult to quantify but relevant for the long-term success of the company in the decision-making process.

With the help of assembly experiments in the Werk150, initial empirical values were gained, allowing the conceived system for configuring and assessing production scenarios to be implemented in practice as a design artefact. The information flow is as follows: First, the assembly organisation forms (individual workstation or line production) are simulated discretely in time for each ordered product type, depending on resource availability. The employees are assigned according to their availability in order to design different variants of production.

Partial cost calculation and the work system value are figured out through two different means: occupancy simulation, for options on the assembly organisation form, and empirical values on the different employee and workplace combinations. The system allows different possibilities for predicting the information. If possible and available, a post-hoc approach considering the average values of past surveys provides an option for the estimation of stress and error rate.

The design artefact was validated through several approaches. The performance of the data collected in the first experiment, and the machine learning approach applied to it, were examined using a train-test split (2/3 to 1/3). In addition, a second experiment was conducted for one of the scenario variants with 5 times the shift duration of the first experiment (4h) to obtain an assessment of the prediction quality and, if necessary, to show how meaningful the data collected in the first experiment were. Finally, the developed concept was applied to another industrial use case in a third experiment to prove the generality and adaptability of the system.

The study concluded by consulting the opinion of several area experts to verify the meaningfulness and relevancy of the assessment logic, the architecture of the configuration, and the rating system.

6.2 Conclusion and some reflection on the results

The research work carried out had a very ambitious goal of creating a digital twin for applicable planning support. A procedure to expand the assessment criteria, its operation, and a system architecture for configuration and assessment for the optimal production scenario was successfully conceived and practically implemented as a digital twin design artefact.

The first research question asked how to extend the decision-making basis of CPPS by means of the EEA. For the rating of CPPS scenarios, a two-sided approach was chosen, with a cost calculation and the work system value, which was derived from literature and close exchange with a research group. Attention was given to relevant aspects that corresponded to the multi-dimensional goals of the Werk150, representing a human-centred small batch production. To the superordinate, purposes of Werk150 count the employee well-being, competence aspects, flexibility aspects, emission avoidance, cost minimization, delivery reliability, capacity utilization and error avoidance, which are represented by the work system value criteria. For the systematic analysis of the work system value criteria, I developed formulas to be implemented in a Python program to allow an automated EEA. The initial information for the calculation consists of already stored general information, such as employee wages or electricity costs. Some information was derived from the results of a discrete-time simulation; some was determined by continuous data collection in the actually implemented factory. The collected data was processed and provided an optional starting point for machine learning application.

In all this, the human being still has a central role to play. Decision-making power belongs to the person, who is free to use the work system value as a decision-making aid. The human in the loop is thus an integral part of the system, and yet the continuous collection of new measurements improves the quality of the planning support provided by the design artefact, making it easier for the human to make good decisions.

With respect to the second research question: the configuration of different CPPS scenarios is determined by the basic scenario and the available resources. The production planner thereby creates different employee allocation scenarios for the different possibilities of the production organization, which also has the potential to randomize. In the choice of agents for the system, the focus in the study was on employees, but the system also permits the use of robots or human-robot collaboration. The agents are currently assigned to workplace-specific work steps, which limits the complexity. In the continuing research process, semi-autonomous variants, which have not yet been applied, are also conceivable in the future. Different sub-aspects, such as the derivation procedure for requirement-based work system value criteria, as well as the continuous learning process—to improve the data situation for data that is difficult to quantify and previously unavailable—offers new application possibilities.

The main novelty of this work and its contribution to the state of the art can be found in the fusion of a learning digital twin and the EEA that takes into account hard-to-measure aspects. The concept, the implementation, and the data situation were critically scrutinised. However, the statistical reliability of the collected data was hampered due to the circumstances. Necessary, fully factual experiments were encumbered by difficulties imposed by contact restrictions. In sum, the project did not receive the desired data basis. Nevertheless, the developed solution was secured with the help of different validation and verification approaches.

6.3 Research limitations and recommendations for further research

First of all, due to the still thin data base, continuous data collection in the Werk150 is necessary in order to ensure the statistical significance of the forecast for the criteria of stress and error potential. The degrees of freedom presented for system design, assembly organisation form, and employee allocation already lead to a large number of scenarios. Nevertheless, the distinction between line production and individual workplace production is a simplification of many systems found in industrial practice. It would therefore be desirable, for example, to include other forms of production organization, such as semi-autonomous group production. To this end, a follow-up work is currently being conducted that seeks to prioritize possible scenario configurations to reduce the computational effort for the scenario simulation. A tool could be developed that preselects from a multitude of variants, independently according to a predefined weighting framework. Further research is also possible when considering the impact horizon, especially with regard to stress in the system, and to long-term consequences.

References

(1) Alibaba AG (2018): ESG-Report 2018.
(2) Alturki, Ahmad; Gable, Guy G.; Bandara, Wasana (2011): A Design Science Research Roadmap. In Hemant Jain, Atish P. Sinha, Padmal Vitharana (Eds.): Service-Oriented Perspectives in Design Science Research, vol. 6629. Berlin, Heidelberg: Springer Berlin Heidelberg (Lecture Notes in Computer Science), pp. 107–123.
(3) Andersen, Ann-Louise; ElMaraghy, Hoda; ElMaraghy, Waguih; Brunoe, Thomas D.; Nielsen, Kjeld (2018): A participatory systems design methodology for changeable manufacturing systems. In *International Journal of Production Research* 56 (8), pp. 2769–2787. DOI: 10.1080/00207543.2017.1394594.
(4) Bartholdt, Luise; Schütz, Astrid (2010): Stress im Arbeitskontext: Ursachen, Bewältigung und Prävention.
(5) Bauernhansl, Thomas; Krüger, Jörg; Reinhart, Gunther; Schuh, Günther (2016): WGP-Standpunkt Industrie 4.0, p. 12.
(6) Besenfelder, Christoph; Brüggenolte, Matthias; Austerjost, Maximilian; Kämmerling, Nicolas; Pöting, Moritz; Dr.-Ing. Christian Schwede; Schellert, Maximilian (2017): Paradigmenwechsel der Planung und Steuerung von Wertschöpfungsnetzen. With assistance of Michael ten Hompel, Michael Henke, Uwe Clausen.
(7) Böckelmann, Irina; Seibt, Reingard (2011): Methoden zur Indikation vorwiegend psychischer Berufsbelastung und Beanspruchung — Möglichkeiten für die betriebliche Praxis. In *Z. Arb. Wiss.* 65 (3), pp. 205–222. DOI: 10.1007/BF03373839.
(8) Boeing, Norbert: Fertigungsorganisation. Fertigungorganisation Lösungen. Unterrichtsdatenbank.de. Available online at https://www.zum.de/Faecher/kurse/boeing/udb/prod/Fertigungsorganisation-Loesung.pdf, checked on 13.11.21.
(9) Bosch GmbH (2018): Sustainability Report 2018 - Spotlight.
(10) Boucsein, W. (1992): Electrodermal Activity: Springer US (The Springer Series in Behavioral Psychophysiology and Medicine).
(11) Boutellier, Urs; Ulmer, Hans-Volkhart (2007): Sport- und Arbeitsphysiologie. In Robert F. Schmidt, Florian Lang (Eds.): Physiologie des Menschen, vol. 47. Berlin, Heidelberg: Springer Berlin Heidelberg (Springer-Lehrbuch), pp. 928–952.
(12) Braglia, Marcello; Petroni, Alberto (2000): Towards a taxonomy of search patterns of manufacturing flexibility in small and medium-sized firms. In *Omega* 28 (2), pp. 195–213. DOI: 10.1016/S0305-0483(99)00044-4.
(13) Bruno, Giulia; Antonelli, Dario (2018): Dynamic task classification and assignment for the management of human-robot collaborative teams in workcells. In *Int J Adv Manuf Technol* 98 (9-12), pp. 2415–2427. DOI: 10.1007/s00170-018-2400-4.
(14) Bullinger, H.-J.; Rally, P. J.; Schipfer, J. (1997): Some aspects of ergonomics in assembly planning. In *International Journal of Industrial Ergonomics* 20 (5), pp. 389–397. DOI: 10.1016/S0169-8141(96)00080-7.
(15) Bullinger, Hans-Jörg; Volkholz, Volker; Betzl, Konrad; Köchling, Annegret; Risch, Wolfram (Eds.) (1993): Alter und Erwerbsarbeit der Zukunft. Berlin, Heidelberg: Springer Berlin Heidelberg.
(16) Burk, Christian (2005): Phasische elektrodermale Aktivität als Persönlichkeitsindikator. Dissertation. Universität Gießen.
(17) Cichon, Torben (2019): The Digital Twin: Mediator for Man-Machine Interaction. RWTH Aachen University.
(18) Deuse, Jochen; Weisner, Kirsten; Hengstebeck, André; Busch, Felix (2015): Gestaltung von Produktionssystemen im Kontext von Industrie 4.0. In Alfons Botthof, Ernst Andreas Hartmann

(Eds.): Zukunft der Arbeit in Industrie 4.0, vol. 108. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 99–109.
(19)DIN 33400:1983-10: Gestalten von Arbeitssystemen nach arbeitswissenschaftlichen Erkenntnissen; Begriffe und allgemeine Leitsätze.
(20)Ding, Kai; Chan, Felix T.S.; Zhang, Xudong; Zhou, Guanghui; Zhang, Fuqiang (2019): Defining a Digital Twin-based Cyber-Physical Production System for autonomous manufacturing in smart shop floors. In *International Journal of Production Research* 57 (20), pp. 6315–6334. DOI: 10.1080/00207543.2019.1566661.
(21)Dogan, Erkan (2021): Arbeitsteilung. Industrial Engineering Vision. Available online at https://industrial-engineering-vision.de/arbeitsteilung/, updated on 6/23/2021, checked on 11/13/2021.
(22)Dr. Hans-Joachim Graf (2019): Einführung in die statistische Versuchsplanung (Design of Experiments / DoE). qtcc. Available online at https://www.youtube.com/watch?v=HctTveRaCZo, updated on 20.06.19, checked on 25.08.21.
(23)Eicher, Corinna (2020): Steuerung zur flexiblen Konfiguration der Inbound-Logistik in der Automobilindustrie. Dissertation. TU München.
(24)ElMaraghy, Hoda A. (2005): Flexible and reconfigurable manufacturing systems paradigms. In *Int J Flex Manuf Syst* 17 (4), pp. 261–276. DOI: 10.1007/s10696-006-9028-7.
(25)Faix, Werner G. (Ed.) (2012): Kompetenz. Festschrift Prof. Dr. John Erpenbeck zum 70. Geburstag. With assistance of John Erpenbeck. 1. Aufl. Stuttgart: Steinbeis-Ed (Talent. Kompetenz. Management, Bd. 4).
(26)Federal Environment Agency (Germany): Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2020. Available online at https://www.umweltbundesamt.de/themen/klima-energie/energieversorgung/strom-waermeversorgung-in-zahlen?sprungmarke=Strommix#Strommix.
(27)Fisel, Johannes (2018): Changeability - a frequency perspective. KIT Karlsruhe. 12th CIRP Conference on Intelligent Computation in Manufacturing Engineering,
(28)Foith-Förster, Petra; Wiedenmann, Marc; Seichter, Dennis; Bauernhansl, Thomas (2016): Axiomatic Approach to Flexible and Changeable Production System Design. In *Procedia CIRP* 53 (2), pp. 8–14. DOI: 10.1016/j.procir.2016.05.001.
(29)Frauenholz, Dieter; Gröger, Vera; Haaren Christina; Schweres, Manfred (2000): Veranschaulichung der Umweltwirkungen landwirtschaftlicher Betriebe –. Konzeption und Anwendungsmöglichkeiten eines computergestützten Verfahrens.
(30)Galizia, Francesco Gabriele; ElMaraghy, Hoda; Bortolini, Marco; Mora, Cristina (2020): Product platforms design, selection and customisation in high-variety manufacturing. In *International Journal of Production Research* 58 (3), pp. 893–911. DOI: 10.1080/00207543.2019.1602745.
(31)Grabner, Thomas (2012): Strukturentwicklung. In Thomas Grabner (Ed.): Operations Management. Wiesbaden: Springer Fachmedien Wiesbaden, pp. 155–186.
(32)Günthner, W. A.; Tenerowicz, P. (2011): Modularisierung und Dezentralisierung in der Intralogistik-Auf dem Weg zur zellularen Fördertechnik. In *Industrie Management* (01), pp. 25–29.
(33)Hasenclever, Tobias; Horenburg, Tim; Höppner, Gerritt; Klaubert, Cornelia; Krupp, Michael; Popp, Karin H. et al. (2011): Logistikmanagement in der Bauwirtschaft. In Willibald Günthner, André Borrmann (Eds.): Digitale Baustelle- innovativer Planen, effizienter Ausführen, vol. 2000. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 205–290.
(34)Hauff, V.; Scharpf, F. W. (1975): Modernisierung der volkswirtschaft. Technologiepolitik als strukturpolitik. Frankfurt am Main: Europaische Verlagsanstalt (Demokratischer sozialismus in theorie und praxis).
(35)Herzog, Jan; Ropke, Hannes; Luder, Arndt (2020 - 2020): Allocation of PPRS for the plant planning in the final automotive assembly. In : 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). Vienna, Austria, 08.09.2020 - 11.09.2020: IEEE, pp. 813–820.

(36)Kache, Martin; Römer, Marcus; Müller, Michael (2015): Leitfaden zur Literaturrecherche. TU Dresden. Available online at https://tu-dresden.de/bu/verkehr/ibb/sft/ressourcen/dateien/lehre/informationen/Leitfaden_Literaturrecherche.pdf?lang=de, checked on 12/21/2021.
(37)Keuntje, Christopher (2019): Integrierte Detailgestaltung von Technik und Prozess innerbetrieblicher Routenzugsysteme für den Transport von Großladungsträgern.
(38)Knauth, Peter: Beanspruchungsmessung. Institut für Industriebetrierbslehre und industrielle Revolution Abt. Arbeitswissenschaft.
(39)KOMMISSION DER EUROPÄISCHEN GEMEINSCHAFTEN (2001): Grünbuch. Europäische Rahmenbedingungen für die soziale Verantwortung der Unternehme. Brüssel.
(40)Kritzinger, Werner; Karner, Matthias; Traar, Georg; Henjes, Jan; Sihn, Wilfried (2018): Digital Twin in manufacturing: A categorical literature review and classification. In *IFAC-PapersOnLine* 51 (11), pp. 1016–1022. DOI: 10.1016/j.ifacol.2018.08.474.
(41)Krüger, Alexander (2004): Planung und Kapazitatsabstimmung stuckzahlflexibler Montagesysteme. Munchen: Utz Herbert.
(42)Langlotz, Pascal; Glatt, Moritz; Sousa, Fábio J. P.; Aurich, Jan C. (2020): Modelle als Grundlage für den Digitalen Zwilling. In *ZWF* 115 (5), pp. 340–343. DOI: 10.3139/104.112281.
(43)Liebrecht, Christoph; Schaumann, Sebastian; Zeranski, Daniel; Antoszkiewicz, Alica; Lanza, Gisela (2018): Analysis of Interactions and Support of Decision Making for the Implementation of Manufacturing Systems 4.0 Methods. In *Procedia CIRP* 73, pp. 161–166. DOI: 10.1016/j.procir.2018.04.005.
(44)Löffler, Carina (2011): Systematik der strategischen Strukturplanung für eine wandlungsfähige und vernetzte Produktion der variantenreichen Serienfertigung. Dissertation. Universität Stuttgart. Graduate School of Excellence advanced Manufacturing Engineering. Available online at https://elib.uni-stuttgart.de/bitstream/11682/4470/1/Diss_Loeffler.pdf, checked on 7/28/2020.
(45)Lotter; Wiendahl, H.-P. (2005): Montage in der industriellen Produktion. Optimierte Abläufe, rationelle Automatisierung. Berlin: Springer (VDI).
(46)März, Lothar; Krug, Wilfried; Rose, Oliver; Weigert, Gerald (2011): Simulation und Optimierung in Produktion und Logistik. Berlin, Heidelberg: Springer Berlin Heidelberg.
(47)Maskell, Brian H.; Kennedy, Frances A. (2007): Why do we need lean accounting and how does it work? In *J. Corp. Acct. Fin.* 18 (3), pp. 59–73. DOI: 10.1002/jcaf.20293.
(48)Mayer, Sebastian; Endisch, Christian (2019 - 2019): Adaptive Production Control in a Modular Assembly System Based on Partial Look-Ahead Scheduling. In : 2019 IEEE International Conference on Mechatronics (ICM). 2019 IEEE International Conference on Mechatronics (ICM). Ilmenau, Germany, 18.03.2019 - 20.03.2019: IEEE, pp. 293–300.
(49)Mayring, Philipp (2010): Qualitative Inhaltsanalyse. In Günter Mey, Katja Mruck (Eds.): Handbuch Qualitative Forschung in der Psychologie. Wiesbaden: VS Verlag für Sozialwissenschaften, pp. 601–613.
(50)Mayring, Philipp; Gläser-Zikuda, Michaela (Eds.) (2008): Die Praxis der Qualitativen Inhaltsanalyse. 2. Aufl. Weinheim: Beltz (Beltz Pädagogik).
(51)Mertens, Ricarda (2016): Aussagekraft der elektrodermalen Aktivität in Laborexperimenten mit Schwerpunkt Lärm. Literaturstudie zu wichtigen Einflussfaktoren und gesundheitlichen Implikationen.
(52)Metzger, Helmut (1977): Planung und Bewertung von Arbeitssystemen in der Montage: Krausskopf.
(53)Michniewicz, Joachim (2019): Automatische simulationsgestützte Arbeitsplanung in der Montage. Technische Universität München.
(54)Monek, Gergő; Szántó, Norbert; Jósvai, János; István, Széchenyi: The Role of Simulation in a Cyber-Physical Production Environment.
(55)Müller, Marcus (2016): Leistungsanreize in der Transportlogistik. Wiesbaden: Springer Fachmedien Wiesbaden.

(56)Neubauer, Günter; Wächter, Hartmut (2011): Extended Profitability Appraisal (EPA) – A first step toward inter-disciplinary planning of innovations. In *Z. Arb. Wiss.* 65 (1), pp. 67–76. DOI: 10.1007/BF03373817.

(57)Ney, Michael (2006): Wirtschaftlichkeit von Interaktionsplattformen. Effizienz und Effektivität an der Schnittstelle zum Kunden. Wiesbaden: Deutscher UniversitSts-Verlag (Gabler Edition Wissenschaft Markt- und Unternehmensentwicklung).

(58)Noehring, Fabian; Woestmann, René; Wienzek, Tobias; Deuse, Jochen (2019): Socio-Technical Capability Assessment to Support Implementation of Cyber-Physical Production Systems in Line with People and Organization. In Isabel L. Nunes (Ed.): Advances in Human Factors and Systems Interaction, vol. 781. Cham: Springer International Publishing (Advances in Intelligent Systems and Computing), pp. 299–311.

(59)Papaestefanou, Georgis (2013): Experimentelle Validierung eines Sensor-Armbandes zur mobilen Messung physiologischer Stress- Reaktionen. Gesis - Leibniz-Institut für Sozialwissenschaften. Available online at https://www.ssoar.info/ssoar/bitstream/handle/document/33949/ssoar-2013-papastefanou-Experimentelle_Validierung_eines_Sensor-Armbandes_zur.pdf?sequence=1&isAllowed=y&lnkname=ssoar-2013-papastefanou-Experimentelle_Validierung_eines_Sensor-Armbandes_zur.pdf, checked on 12/12/2021.

(60)Paton, Frieda (2018): Breaks During Work Are Necessary for Employee Well-Being and Work Performance. workplacetesting.com. Available online at https://www.workplacetesting.com/2/2977/wellness/breaks-during-work-are-necessary-for-employee-well-being-and-work-performance, updated on 7/16/2018, checked on 12/5/2021.

(61)Pawlikowski, Maciej: How to Predict Potential Errors in The Early Production Process? Available online at https://stermedia.ai/how-to-predict-potential-errors-in-the-early-production-process-with-ai/, checked on 21.12.21.

(62)Pitsch, Udo; Pitsch, Ines (2014): Ein Weg zum Marathon. Dritter Teil: Trainingsformen für den Marathon. Pitsch-Aktiv. Available online at http://marathon.pitsch-aktiv.de/e-wzm/ewzm-3.html, updated on 11/30/2021, checked on 12/5/2021.

(63)Pröpster, Markus Hubert (2015): Methodik zur kurzfristigen Austaktung variantenreicher. Dissertation. Technische Universität München, München. Lehrstuhl für Betriebswissenschaften und Montagetechnik.

(64)Ranz, Fabian; Hummel, Vera; Sihn, Wilfried (2017): Capability-based Task Allocation in Human-robot Collaboration. In *Procedia Manufacturing* 9, pp. 182–189. DOI: 10.1016/j.promfg.2017.04.011.

(65)Reichwald, Ralf; Höfer, Claudia; Weichselbaumer, Jürgen (1996): Erfolg von Reorganisationsprozessen: Leitfaden zur strategieorientierten Bewertung: Schäffer-Poeschel.

(66)Reutlingen University: Research online course Reutlingen University. Available online at https://www.reutlingen-university.de/en/while-studying/learning-centre/service-desk-consultations-and-courses/research-online-course/, checked on 21.12.21.

(67)Rohmert, W.; Luczak, H. (1975): Faktorenanalytische Auswertung einer Befragung zu Gesundheits- und Beanspruchungsempfinden sowie Arbeitszufriedenheit von Bahnpostbegleitern. In *International archives of occupational and environmental health* 36 (2), pp. 105–118. DOI: 10.1007/BF01262316.

(68)Sauer, Olaf (2020): Von der Werkstattfertigung zur Selbstorganisation. Fraunhofer IOSB. Available online at https://www.it-production.com/fertigungsnahe-it/fertigungsorganisation/, updated on 5/19/2020, checked on 11/13/2021.

(69)Schlick, Christopher; Luczak, H.; Bruder, Ralph (2010): Arbeitswissenschaft. 3., volständig überarbeitete und erw. Aufl. Heidelberg: Springer.

(70)Schlink, Haiko (2019): Wirtschaftlichkeitsrechnung für Ingenieure. Wiesbaden: Springer Fachmedien Wiesbaden.

(71)Schmidt, Robert F.; Thews, Gerhard (1977): Physiologie des Menschen. Berlin, Heidelberg: Springer Berlin Heidelberg.

(72)Schröter, D.; Jaschewski, P.; Kuhrke, B.; Verl, A. (2016): Methodology to Identify Applications for Collaborative Robots in Powertrain Assembly. In *Procedia CIRP* 55, pp. 12–17. DOI: 10.1016/j.procir.2016.08.015.
(73)Schuller, Björn (2006): Automatische Emotionserkennung aus sprachlicher und manueller Interaktion. Dissertation Dr.-Ing. TU Munich.
(74)Schultetus, Wolfgang (2006): Arbeitswissenschaft, von der Theorie zur Praxis. Arbeitswissenschaftliche Erkenntnisse und ihr wirtschaftlicher Nutzen. Köln: Wirtschaftsverl. Bachem.
(75)Sengotta, M.; Roesler, J.; Schweres, M. (1997): Arbeitssystemcontrolling. In *ZWF* 92 (12), pp. 647–650. DOI: 10.1515/zwf-1997-921218.
(76)Sengotta, M.; Schweres, M. (1994): Entwicklung und Evaluation eines Verfahrens der erweiterten Wirtschaftlichkeitsrechnung zur Bewertung komplexer Arbeitssysteme: Wirtschaftsverl. NW, Verlag für Neue Wiss (Schriftenreihe der Bundesanstalt für Arbeitsschutz / Forschung: Forschung). Available online at https://books.google.co.za/books?id=0QZuNQAACAAJ.
(77)Siedenbiedel, Georg (2020): Gestaltung organisationaler Strukturen. In Georg Siedenbiedel (Ed.): Organisationale Gestaltung. Wiesbaden: Springer Fachmedien Wiesbaden, pp. 97–178.
(78)Sozialmedizinisches Glossar.
(79)Tesla AG (2019): Impact Report.
(80)Thommen, Jean-Paul; Achleitner, Ann-Kristin; Gilbert, Dirk Ulrich; Hachmeister, Dirk; Jarchow, Svenja; Kaiser, Gernot (2020): Gestaltung der Produktionsprozesse. In Jean-Paul Thommen, Ann-Kristin Achleitner, Dirk Ulrich Gilbert, Dirk Hachmeister, Svenja Jarchow, Gernot Kaiser (Eds.): Allgemeine Betriebswirtschaftslehre. Wiesbaden: Springer Fachmedien Wiesbaden, pp. 197–204.
(81)Trougakos, John P.; Hideg, Ivona (2009): Momentary work recovery: The role of within-day work breaks. In Sabine Sonnentag, Pamela L. Perrewé, Daniel C. Ganster (Eds.): Current Perspectives on Job-Stress Recovery, vol. 7: Emerald Group Publishing Limited (Research in Occupational Stress and Well-being), pp. 37–84.
(82)Uhlemann, Thomas H.-J.; Lehmann, Christian; Steinhilper, Rolf (2017): The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0. In *Procedia CIRP* 61, pp. 335–340. DOI: 10.1016/j.procir.2016.11.152.
(83)Vaishnavi, Vijay; Kuechler, B. (2004): Design Science Research in Information Systems. In *Association for Information Systems*.
(84)Vaishnavi, Vijay; Kuechler, Bill; Petter, Stacie (2019): Design Science Research in Information Systems. Available online at http://desrist.org/desrist/content/design-science-research-in-information-systems.pdf, checked on 11/6/2021.
(85)Venn, Eric (2010): Beitrag zur simulationsgestützten Konzeptplanung von heterogen strukturierten Kommissioniersystemen. Dissertation. Universität Duisburg-Essen, Duisburg-Essen. Fakultät für Ingenieurswesen.
(86)Westkämper, Engelbert; Löffler, Carina (2016): Strategien der Produktion. Berlin, Heidelberg: Springer Berlin Heidelberg.
(87)Westkämper, Engelbert; Zahn, Erich (2009): Wandlungsfähige Produktionsunternehmen. Berlin, Heidelberg: Springer Berlin Heidelberg.
(88)Wiendahl, H.-P.; ElMaraghy, H. A.; Nyhuis, P.; Zäh, M. F.; Wiendahl, H.-H.; Duffie, N.; Brieke, M. (2007): Changeable Manufacturing - Classification, Design and Operation. In *CIRP Annals* 56 (2), pp. 783–809. DOI: 10.1016/j.cirp.2007.10.003.
(89)Wiendahl, Hans-Peter; Wiendahl, Hans-Hermann (2020): Betriebsorganisation für Ingenieure. 9., vollständig überarbeitete Auflage. München: Hanser.
(90)Willnecker, Ulrich (2000): Gestaltung und Planung leistungsorientierter manueller Fließmontagen. Dissertation Phd. TU München, München. Maschinenwesen.
(91)Wulf, Serjosha; Nyhuis, Peter (2008): Integrative Werksentwicklung. In *ZWF* 103 (10), pp. 656–660. DOI: 10.3139/104.101338.

(92)Xiong, Feng; Xu, Si; Zheng, Dongzhu (2020): An investigation of the uber driver reward system in china – an application of a dynamic pricing model. In *Technology Analysis & Strategic Management* 56, pp. 1–14. DOI: 10.1080/09537325.2020.1787975.
(93)Zäh, M. F.; Moeller W.; Vogl W. (2005): Symbiosis of Changeable and Virtual Production – The Emperor's New Clothes or Key Factor for Future Success?
(94)Zammori, F.; Braglia, M.; Frosolinia, M. (2011): A measurement method of routing flexibility in manufacturing systems. In *IJIEC*, pp. 593–616. DOI: 10.5267/j.ijiec.2011.03.001.
(95)Zhang, Haijun; Zhang, Guohui; Yan, Qiong (2019): Digital twin-driven cyber-physical production system towards smart shop-floor. In *J Ambient Intell Human Comput* 10 (11), pp. 4439–4453. DOI: 10.1007/s12652-018-1125-4.

Appendix A

The appendix contains information for scenario planning and data that will be used as a basis for the description model of the developed design artefact. The following table shows the component list, which contains the availability of components in the Werk150 and must be considered when configuring scenarios, as it may not be possible to implement certain basic scenarios if components are not available.

Table 42: List of components (Flex Blue)

Abbreviation	Number	Description
CN01	1	CNC machining centre EMCO
RO01 - RO09	9	M/R collaborative roboter
GR01	1	Robotiq gripper 2F - 85
MP01 - MP05	5	Mobile platform
KR01	1	collaborative trugger train
FC1 - FC12	12	Flex conveyor short
FC13 - FC18	6	Flex conveyor long
FC19 - FC25	7	Flex conveyor converter
WZ01 - WZ06	6	Bosch screwdriver
VR02 - VR09	8	Fixture f. microset
VR12-16	je 1	Fixture f. Bewatec scooter
VR17	?	Mounting device
VR11	?	Mounting device
	1	Airpump

A.1 General info as data basis of the description model

For the description model of the design artefact, different information is needed so that the calculations can be carried out. This information includes an assumed value for the electricity price, which is assumed to be an estimated cost of 0.32€ per kWh. To derive the CO2 emissions from the electricity, the value of the German electricity mix (kg CO2/kWh): 0.401 is assumed.

Table 43: Assumed wage costs

Person (P)	Wage [€/h]
P1	25
P2	25
P3	30
P4	20
P5	35

Table 44: Opportunity cost and Energy consumption of WP

Workplace	Depreciation (€/day)	Total Machine Costfactor (Opport. Cost and Depreciation) (€/h)	Power consumption active [kW/h]	Changeover times [min]
FB_order picking	2	10	1	10
FB_assembly base	2	10	1	10
FB_assembly stem	2	10	1	10
FB_wedding	2	10	1	10
FB_individual wp	2	10	1	25
BS_assembly base	2	10	1	15
BS_assembly stem	2	10	1	15
BS_wedding	2	10	1	15
BS_individual wp	3	15	1	30

Table 45: Value added (va) at WP (assuming va of FlexBlue = 12 and va of BeewSil = 60)

	value added
workplace	va/piece
FB_order picking	3
FB_assembly base	3
FB_assembly stem	3
FB_wedding	3
FB_individual wp	12
BS_assembly base	20
BS_assembly stem	20
BS_wedding	20
BS_individual wp	60

Table 46: Requirement profiles of the work steps (expert estimate) for the competence delta on the scale: 1 (low) - 5(high)

Type of competence	FB order picking	FB base	FB stem	FB wedding	FB individual wp	BS base	BS stem	BS wedding	BS individual wp
Personal responsibility	1	1	1	4	5	3	3	3	5
Commitment	4	4	4	3	5	5	5	5	5
Adaptability	3	2	2	2	5	3	3	5	5
Diligence	4	4	4	4	3	4	4	4	4
Problem-solving ability	2	3	2	5	5	5	5	5	5
Ability to judge	1	1	2	2	5	2	2	4	3
Perseverance	2	2	2	1	4	4	4	5	5

Table 47: Competence profiles of the employees (self-assessment)

Type of competence	P1	P2	P3	P4	P5
Personal responsibility	5	5	3	3	4
Commitment	3	5	4	5	2
Adaptability	4	3	2	1	2
Diligence	3	3	1	5	5
Problem-solving ability	2	2	2	3	5
Ability to judge	2	3	4	5	2
Perseverance	1	2	5	2	2

A.2 Evaluation and transfer of the experimental fitness tracker data

In the following, programme code is presented that helps to evaluate the raw measured values with the Wellue Ring, to bring them into a uniform and comparable form and to save them. In particular, interruptions in the recording or the splitting of recordings in order to assign measured values directly to the individual shifts could be achieved in this way.

```
def werk150():
    path = 'Manu/Versuch2 Werk150/Timur (9970) - Kopie'  # path to the csv files of the current worker
    all_files = glob.glob(path + "/*.csv")
    print(path.split('/')[-1])  # name of current worker
    dataframes = []

    # load all files to dataframes
    for filename in all_files:
        data = pd.read_csv(filename, index_col=None, header=0)
        dataframes.append(data)

    # concatenate all dataframes
    dataframe = pd.concat(dataframes, axis=0, ignore_index=True)

    # indices where the 45min shifts starts and stops
    start_index = [0, 720, 1410, 2130, 2850]
    stop_index = [675, 1365, 2085, 2805, 3525]

    # print statistical information for each shift
    for start, stop in zip(start_index, stop_index):
        print('--------------------------------------------------------------')

        # get values of current shift
        df = dataframe.drop(dataframe[dataframe.index < start].index)
        df = df.drop(df[df.index > stop].index)

        # filter outliers
        df = df.drop(df[df.Sp02 > 250].index)
        df.drop(df[df.Pulsfrequenz > 500].index)

        # print statistics
        print('index from ' + str(start) + ' to ' + str(stop))
        print(df.describe())
    print('--------------------------------------------------------------')
```

Figure 103: Programme for analysing the raw data from the fitness trackers (example of 2 experiments in Werk150)

```python
def vine_bottling():
    path = 'Manu/Versuch Weinabfüllung/P10 (Steffen) - Kopie'  # path to the csv files of the current worker
    path1 = path + '/1'
    path2 = path + '/2'

    # -------------------- shift 1 ------------------------------
    all_files = glob.glob(path1 + "/*.csv")
    dataframes = []

    # load all files to dataframes
    for filename in all_files:
        data = pd.read_csv(filename, index_col=None, header=0)
        dataframes.append(data)

    # concatenate all dataframes
    dataframe = pd.concat(dataframes, axis=0, ignore_index=True)

    print('--------------------- shift 1 ------------------------------')
    print(path.split('/')[-1])  # name of current worker

    # filter outliers
    dataframe.drop(dataframe[dataframe.SpO2 > 250].index, inplace=True)
    dataframe.drop(dataframe[dataframe['Pulse Rate'] > 500].index, inplace=True)

    # print statistics
    print(dataframe.describe())

    # -------------------- shift 2 ------------------------------
    all_files = glob.glob(path2 + "/*.csv")
    dataframes = []

    for filename in all_files:
        df = pd.read_csv(filename, index_col=None, header=0)
        dataframes.append(df)
    dataframe = pd.concat(dataframes, axis=0, ignore_index=True)
    print('--------------------- shift 2 ------------------------------')
    print(path.split('/')[-1])  # name of current worker

    # filter outliers
    dataframe.drop(dataframe[dataframe.SpO2 > 250].index, inplace=True)
    dataframe.drop(dataframe[dataframe['Pulse Rate'] > 500].index, inplace=True)

    # print statistics
    print(dataframe.describe())
    print('-------------------------------------------------------------')

vine_bottling()
werk150()
```

Figure 104: Programme for evaluating the raw data of the fitness trackers (example wine bottling)

A.3 Detailed results for the different criteria of the example scenarios S1-12

```
mental stress in %: 60.276505250503185
physical stress in %: 72.80503465423183
error potential in %: 72.635
competence fit in %:  85.51076230636156
delivery reliability in %:  100.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  1305.4180033333332
total co2 [kg]:  13.5949
work system value in %:  76.12770983968048
```

Figure 105: Detailed rating result for example scenario S1

```
mental stress in %: 68.99057734885876
physical stress in %: 71.9912614289182
error potential in %: 76.25833333333334
competence fit in %:  69.91032001146087
delivery reliability in %:  100.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  1356.0692533333333
total co2 [kg]:  13.5949
work system value in %:  75.54530839846255
```

Figure 106: Detailed rating result for example scenario S2

```
mental stress in %: 73.13110063332574
physical stress in %: 92.36831458855895
error potential in %: 97.925
competence fit in %:  82.44869837393504
delivery reliability in %:  100.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  1404.913003333333
total co2 [kg]:  13.5949
work system value in %:  83.93425432321236
```

Figure 107: Detailed rating result for example scenario S3

```
mental stress in %: 46.36666035233946
physical stress in %: 79.02345141125213
error potential in %: 88.7125
competence fit in %:  69.04412632262604
delivery reliability in %:  50.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  2678.4493333333335
total co2 [kg]:  26.395000000000003
work system value in %:  67.83048639326918
```

Figure 108: Detailed rating result for example scenario S4

```
mental stress in %: 44.675430952831974
physical stress in %: 74.9344951695397
error potential in %: 92.5
competence fit in %:  68.94183422184938
delivery reliability in %:  50.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  2683.9393333333337
total co2 [kg]:  26.395000000000003
work system value in %:  67.53120385869825
```

Figure 109: Detailed rating result for example scenario S5

```
mental stress in %: 33.28160636484183
physical stress in %: 67.2859253646524
error potential in %: 45.85
competence fit in %:  61.610976104781756
delivery reliability in %:  50.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  2673.2743333333337
total co2 [kg]:  26.395000000000003
work system value in %:  57.0993106429918
```

Figure 110: Detailed rating result for example scenario S6

```
mental stress in %: 76.43934109994699
physical stress in %: 48.86350501986823
error potential in %: 80.0
competence fit in %:  81.1870087149976
delivery reliability in %:  50.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  2274.4563233333333
total co2 [kg]:  27.705300000000005
work system value in %:  68.30807450021136
```

Figure 111: Detailed rating result for example scenario S7

```
mental stress in %: 48.596622306923216
physical stress in %: 79.72142514248175
error potential in %: 66.68333333333334
competence fit in %:  76.88902484362197
delivery reliability in %:  50.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  2555.3975733333336
total co2 [kg]:  27.705300000000005
work system value in %:  66.22243889900385
```

Figure 112: Detailed rating result for example scenario S8

```
mental stress in %: 63.218301191468775
physical stress in %: 70.19949251587241
error potential in %: 100.0
competence fit in %:  75.4887873439378
delivery reliability in %:  50.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  2593.1263233333334
total co2 [kg]:  27.705300000000005
work system value in %:  71.51046395970653
```

Figure 113: Detailed rating result for example scenario S9

```
mental stress in %: 60.38325754096985
physical stress in %: 59.61674245903015
error potential in %: 100.0
competence fit in %:  73.66724295667103
delivery reliability in %:  0.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  3625.2576533333336
total co2 [kg]:  40.50540000000001
work system value in %:  62.190558517619664
```

Figure 114: Detailed rating result for example scenario S10

```
mental stress in %: 30.191628770484925
physical stress in %: 70.19162877048493
error potential in %: 33.35
competence fit in %:  68.76305734191351
delivery reliability in %:  0.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  3883.267653333334
total co2 [kg]:  40.50540000000001
work system value in %:  49.16614022136429
```

Figure 115: Detailed rating result for example scenario S11

```
mental stress in %: 50.19162877048492
physical stress in %: 69.80837122951507
error potential in %: 100.0
competence fit in %:  68.57142857142858
delivery reliability in %:  0.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  3883.267653333334
total co2 [kg]:  40.50540000000001
work system value in %:  61.46258503401361
```

Figure 116: Detailed rating result for example scenario S12

A.4 Overview of the measured values and examples of the recorded times

The purpose of this section is to provide a sample overview of the data collected. The data collected from the fitness trackers, the feedback on stress and the reject rates are stored for the first and second test series in Werk150 with shift durations of 45 minutes and 4 hours respectively and the shifts for bottling wine. The recorded times are shown as an example for the 2nd test in Werk150. Due to lack of space and poor readability, the rest of the data is not shown here. However, they will be handed in together with the programmed Python code for the submission of the thesis.

Table 48: Color assignment (legend) of the data to the shifts

Experiment	shift times
1 (Werk150)	45min
2 (Werk150)	45min (5 times in a row)
3 (Wine bottling)	(1:18h)
4 (Wine bottling)	(5:03h)

Table 49: Data from the first experimental runs in the Werk150

Person	workplace	av_spo	min_spo2	av_heartr	min_heartrate	max_heartr	rejects	mental_str	physical_st	general_stre
P1	FB_assembly stem	95	93	96	75	120	0	3	4	4
P1	FB_assembly base	95	93	93	80	113	0.125	3	4	4
P1	FB_wedding	95	92	101	85	122	0.16666666	5	5	5
P1	FB_individual wp	96	94	102	85	120	0.33333333	2	4	3
P1	BS_assembly stem	95	92	91	75	105	1	1	4	3
P1	BS_assembly base	96	94	93	85	112	0	1	4	3
P1	BS_wedding	96	93	91	75	102	0	3	5	4
P1	BS_individual wp	95	92	86	72	100	0	2	4	3
P2	FB_order picking	96	92	77	63	99	0	2	2	3
P2	FB_assembly stem	96	92	79	62	92	0	3	3	4
P2	FB_assembly base	96	93	75	60	90	0.2	2	3	3
P2	FB_wedding	96	93	75	52	91	0.2	4	4	3
P2	FB_individual wp	96	94	87	68	105	0	3	3	3
P2	BS_individual wp	97	95	81	63	96	1	1	3	1
P3	FB_order picking	96	94	97	72	120	0	5	3	5
P3	FB_assembly base	96	93	92	65	120	0	2	4	3
P3	FB_wedding	96	94	88	62	120	0.16666666	4	5	5
P3	FB_individual wp	96	90	93	62	118	0	3	4	4
P3	BS_assembly stem	96	92	83	58	97	0	3	5	5
P3	BS_assembly base	95	92	85	60	112	0	4	5	4
P3	BS_wedding	96	93	87	45	105	1	5	5	3
P4	FB_order picking	95	91	89	70	105	0	4	3	4
P4	FB_assembly stem	96	88	98	76	120	0.16666666	3	4	3
P4	FB_individual wp	95	91	96	75	112	0	4	2	4
P4	BS_assembly stem	95	90	93	75	108	0	4	4	4
P4	BS_assembly base	95	92	88	65	112	0	2	4	4
P4	BS_wedding	97	94	94	80	115	0	2	3	3
P5	FB_order picking	95	91	85	73	115	0	5	5	5
P5	FB_assembly stem	96	93	87	74	110	0.4	2	1	2
P5	FB_assembly base	96	94	80	56	104	0.57142857	4	4	4
P5	FB_wedding	96	94	91	80	105	0.2	4	2	3
P5	FB_individual wp	95	93	80	68	100	0	5	5	5
P5	BS_assembly stem	95	93	78	65	100	0	3	5	4
P5	BS_assembly base	96	94	82	70	115	0	5	5	5
P5	BS_wedding	95	88	79	50	95	1	3	4	4

Table 50: Data from the second experimental runs in the Werk150

Person	workplace	av_spo2	min_spo2	av_heartrate	min_heartrate	max_heartrate	rejects	mental_stress	physical_stress	general_stres
P1	FB_order picking	94,8	93	92,7	71	113	0	4	4	4
P1	FB_order picking	95,1	94	93,7	72	113	0	4	4	4
P1	FB_order picking	94,5	93	86,2	65	104	0	4	4	4
P1	FB_order picking	94,7	93	84,8	72	102	0	4	4	4
P1	FB_order picking	94,3	91	87,6	65	103	0	4	4	4
P3	FB_wedding	95,7	92	92,1	70	114	1/8	3	5	4
P3	FB_wedding	96,5	94	84,1	69	105	0	4	5	4
P3	FB_wedding	96,5	94	82,6	59	102	0	5	5	5
P3	FB_wedding	96,4	94	81	64	108	1/3	3	5	4
P3	FB_wedding	96,1	94	86,3	59	120	2/7	2	4	3
P4	FB_assembly stem	95,6	94	98,4	74	138	0	4	5	4
P4	FB_assembly stem	95	93	90,8	71	112	0	4	4	4
P4	FB_assembly stem	95,1	93	81,7	65	115	1/9	4	4	4
P4	FB_assembly stem	95,3	94	87,6	67	113	0	4	4	4
P4	FB_assembly stem	95,7	94	96,6	74	120	0	4	3	4
P6	FB_assembly base	95,7	93	83,3	62	97	0	4	4	4
P6	FB_assembly base	95,2	93	82,6	65	102	0	4	4	4
P6	FB_assembly base	95,1	93	84,4	65	108	0	4	3	4
P6	FB_assembly base	94,2	91	86,1	58	110	0	3	3	3
P6	FB_assembly base	95,8	93	84	64	97	0	3	2	3

Table 51: Recorded times from the second experimental runs in the Werk150

AP_Kommisionierung		**P1**	
Beginn Zeit	Ende Zeit	Dauer	Wartezeit
00:00:00	00:05:30	00:05:30	00:00:15
00:05:45	00:08:41	00:02:56	00:02:44
00:11:25	00:16:05	00:04:40	00:01:08
00:17:13	00:20:36	00:03:23	00:00:38
00:21:14	00:24:24	00:03:10	00:01:16
00:25:40	00:29:23	00:03:43	00:03:15
00:32:38	00:36:20	00:03:42	00:02:00
00:38:20	00:41:45	00:03:25	00:03:15
00:45:00			
Pause (3min)			
00:48:00	00:52:35	00:04:35	00:01:34
00:54:09	00:59:38	00:05:29	00:02:39
01:02:17	01:06:58	00:04:41	00:01:07
01:08:05	01:12:27	00:04:22	00:06:26
01:18:53	01:22:27	00:03:34	00:02:52
01:25:19	01:28:52	00:03:33	00:01:08
01:30:00	01:33:00	00:03:00	00:00:00
01:33:00			
Pause (3min)			
01:36:00	01:38:59	00:02:59	00:01:01
01:40:00	01:45:20	00:05:20	00:01:09
01:46:29	01:49:29	00:03:00	00:00:59
01:50:28	01:53:19	00:02:51	00:00:01
01:53:20	01:56:59	00:03:39	00:00:44
01:57:43	02:01:09	00:03:26	00:03:18
02:04:27	02:10:50	00:06:23	00:03:10
02:14:00	02:18:41	00:04:41	00:02:19
02:21:00			
Pause (3min)			
02:24:00	02:28:45	00:04:45	00:06:45
02:35:30	02:39:00	00:03:30	00:00:27
02:39:27	02:42:24	00:02:57	00:02:53
02:45:17	02:48:30	00:03:13	00:02:54
02:51:24	02:54:25	00:03:01	00:03:01
02:57:26	03:01:29	00:04:03	00:02:30
03:03:59	03:06:45	00:02:46	00:02:15
03:09:00			
Pause (3min)			
03:12:00	03:17:28	00:05:28	00:03:09
03:20:37	03:24:05	00:03:28	00:01:24
03:25:29	03:30:26	00:04:57	00:00:39
03:31:05	03:35:38	00:04:33	00:03:18
03:38:56	03:42:01	00:03:05	00:03:19
03:45:20	03:50:52	00:05:32	00:01:17
03:52:09	03:54:48	00:02:39	00:00:02
03:54:50	03:57	00:02:10	
		00:03:54	00:02:05

AP_Vorbau		**P4**	
Beginn Zeit	Ende Zeit	Dauer	Wartezeit
00:00:00	00:06:43	00:06:43	00:00:07
00:06:50	00:14:16	00:07:26	00:00:05
00:14:21	00:18:54	00:04:33	00:00:06
00:19:00	00:23:55	00:04:55	00:00:05
00:24:00	00:30:39	00:06:39	00:00:04
00:30:43	00:35:46	00:05:03	00:00:04
00:35:50	00:42:20	00:06:30	00:00:04
00:42:24			
00:45:00			
Pause (3min)			
00:48:00	00:51:15	00:03:15	00:00:05
00:51:20	00:59:53	00:08:33	00:00:01
00:59:54	01:05:16	00:05:22	00:00:04
01:05:20	01:10:34	00:05:14	00:00:30
01:11:04	01:15:41	00:04:37	00:00:40
01:16:21	01:23:15	00:06:54	00:00:06
01:23:21	01:28:30	00:05:09	00:00:04
01:28:34	01:38:00	00:09:26	
Pause (3min)			
01:36:00	01:40:44	00:04:44	00:00:07
01:40:51	01:45:52	00:05:01	00:00:05
01:45:57	01:50:34	00:04:37	00:00:07
01:50:41	01:55:54	00:05:13	00:00:08
01:56:02	02:01:18	00:05:16	00:00:06
02:01:24	02:06:24	00:05:00	00:00:04
02:06:28	02:12:22	00:05:54	00:00:04
02:12:26	02:17:37	00:05:11	00:00:05
02:17:42	02:21	00:03:18	
Pause (3min)			
02:24:00	02:31:41	00:07:41	00:00:05
02:31:46	02:38:30	00:06:44	00:00:05
02:38:35	02:44:01	00:05:26	00:00:05
02:44:06	02:50:17	00:06:11	00:00:06
02:50:23	02:56:31	00:06:08	00:00:06
02:56:37	03:03:55	00:07:18	00:00:04
03:03:59	03:09:00	00:05:01	
Pause (3min)			
03:12:00	03:12:53	00:00:53	00:00:47
03:13:40	03:18:38	00:04:58	00:00:23
03:19:01	03:24:50	00:05:49	00:04:12
03:29:02	03:30:34	00:01:32	00:00:33
03:31:07	03:38:58	00:07:51	00:00:12
03:39:10	03:44:40	00:05:30	00:00:10
03:44:50	03:50:40	00:05:50	00:00:05
03:50:45	03:55:18	00:04:33	00:00:08
03:55:26	03:57:00	00:01:34	
		00:05:26	00:00:16

AP_Unterbau		**P6**	
Beginn Zeit	Ende Zeit	Dauer	Wartezeit
00:00:00	00:07:07	00:07:07	00:00:14
00:07:21	00:11:09	00:03:48	00:00:48
00:11:57	00:16:24	00:04:27	00:00:16
00:16:40	00:19:31	00:02:51	00:00:22
00:19:53	00:22:04	00:02:11	00:02:13
00:24:17	00:28:42	00:04:25	00:00:14
00:28:56	00:33:57	00:05:01	00:02:47
00:36:44	00:39:23	00:02:39	00:02:11
00:41:34			
00:45:00			
Pause(3min)			
00:48:00	00:51:30	00:03:30	00:00:47
00:52:17	00:55:12	00:02:55	00:05:49
01:01:01	01:04:04	00:03:03	00:02:17
01:06:21	01:11:20	00:04:59	00:00:08
01:11:28	01:16:01	00:04:33	00:01:00
01:17:01	01:21:54	00:04:53	00:00:27
01:22:21	01:25:52	00:03:31	00:03:08
01:29:00	01:31:34	00:02:34	
Pause(3min)			
01:38:49	01:40:46	00:01:57	00:00:38
01:41:24	01:44:44	00:03:20	00:00:54
01:45:38	01:48:26	00:02:48	00:00:35
01:49:01	01:51:51	00:02:50	00:00:19
01:52:10	01:55:37	00:03:27	00:00:23
01:56:00	01:58:38	00:02:38	00:00:09
01:58:47	02:02:21	00:03:34	00:00:17
02:02:38	02:06:47	00:04:09	
Pause(3min)			
02:24:00	02:27:41	00:03:41	00:00:29
02:28:10	02:32:01	00:03:51	00:00:18
02:32:19	02:36:15	00:03:56	00:02:43
02:38:58	02:41:37	00:02:39	00:00:22
02:41:59	02:46:25	00:04:26	00:02:43
02:49:08	02:53:58	00:04:50	00:00:13
02:54:11	02:56:56	00:02:45	00:00:17
02:57:13	03:01:48	00:04:35	00:00:27
03:02:15	03:06:15	00:04:00	00:00:25
03:06:40	03:09:27	00:02:47	
Pause(3min)			
03:13:40	03:15:42	00:02:02	00:00:08
03:15:50	03:18:15	00:02:25	00:00:15
03:18:30	03:21:00	00:02:30	00:00:10
03:21:10	03:24:15	00:03:05	00:00:34
03:24:49	03:28:40	00:03:51	00:02:24
03:31:04	03:35:29	00:04:25	00:00:20
03:35:49	03:38:40	00:02:51	00:00:21
03:39:01	03:41:30	00:02:29	00:00:40
03:42:10	03:46:25	00:04:15	00:00:25
03:46:50	03:49:22	00:02:32	00:02:10
03:51:32	03:53:23	00:01:51	00:00:27
03:53:50	03:57:00	00:03:10	
		00:03:29	00:01:00

AP_Hochzeit		**P3**	
Beginn Zeit	Ende Zeit	Dauer	Wartezeit
00:00:00	00:04:20	00:04:20	00:02:40
00:07:00	00:10:50	00:03:50	00:03:10
00:14:00	00:18:20	00:04:20	00:00:25
00:18:45	00:23:40	00:04:55	00:00:30
00:24:10	00:29:10	00:05:00	00:02:20
00:31:30	00:36:00	00:04:30	00:00:00
00:36:00	00:41:10	00:05:10	00:01:10
00:42:20	00:45:00	00:02:40	
Pause (3min)			
00:51:00	00:56:00	00:05:00	00:04:00
01:00:00	01:03:10	00:03:10	00:01:50
01:05:00	01:08:00	00:03:00	00:03:00
01:11:00	01:13:15	00:02:15	00:02:45
01:16:00	01:20:00	00:04:00	00:05:30
01:25:30	01:27:30	00:02:00	00:01:00
01:28:30	01:30:30	00:02:00	
Pause (3min)			
01:38:00	01:39:00	00:01:00	00:00:30
01:39:30	01:41:30	00:02:00	00:00:30
01:42:00	01:45:45	00:03:45	00:00:15
01:46:00	01:50:08	00:04:08	00:02:12
01:52:20	01:57:50	00:05:30	00:00:10
01:58:00	01:59:00	00:01:00	00:03:45
02:02:45	02:06:00	00:03:15	00:10:05
02:16:05	02:19:55	00:03:50	
Pause (3min)			
02:27:40	02:30:30	00:02:50	00:01:30
02:32:00	02:37:00	00:05:00	00:00:10
02:37:10	02:40:30	00:03:20	00:01:20
02:41:50	02:45:30	00:03:40	00:02:00
02:47:30	02:51:20	00:03:50	00:02:50
02:54:10	02:57:30	00:03:20	00:00:20
02:57:50	03:00:50	00:03:00	00:02:40
03:03:30	03:05:50	00:02:20	00:00:10
03:06:00	03:09:00	00:03:00	
Pause (3min)			
03:13:50	03:16:30	00:02:40	00:00:00
03:16:30	03:17:50	00:01:20	00:05:50
03:23:40	03:25:00	00:01:20	00:10:40
03:35:40	03:38:30	00:02:50	00:00:20
03:38:50	03:41:50	00:03:00	00:00:10
03:42:00	03:45:20	00:03:20	00:05:30
03:50:50	03:53:20	00:02:30	
		00:03:17	00:02:20

Table 52: Data from the experimental runs for wine bottling

Person	workplace	av_spo2	min_spo2	av_heartr	min_hear	max_hear	rejects	mental_st	physical_s	general_s
P1	WB_Sulfurizing	95,2	88	87,8	57	114	0	5	3	4
P1	WB_Sulfurizing	94,8	89	80,5	55	113	0	5	3	4
P1	WB_Ind WP	95,1	90	81,3	58	121	0	4	3	4
P7	WB_Equip	91,9	81	74	54	93	0	4	4	4
P7	WB_Equip	94,9	89	80,5	55	113	0	4	4	4
P8	WB_Removal	96,2	93	91	68	116	0	5	5	5
P8	WB_Removal	95,6	93	84,4	57	124	0	5	5	5
P9	WB_Bolting	93,1	89	87,3	64	114	0	5	4	4
P9	WB_Bolting	95,4	90	86,8	64	120	0	4	4	4
P10	WB_Put away	96,3	92	94	69	139	0	5	4	4
P10	WB_Put away	95,8	90	83,8	57	124	0	5	4	4