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Master Production Scheduling with Consideration of Utilization-Dependent Exhaustion and Capacity Load

Marco Trost [1,*], Thorsten Claus [1] and Frank Herrmann [2]

[1] International Institute (IHI) Zittau, Technische Universität Dresden, Markt 23, 02763 Zittau, Germany; thorsten.claus@tu-dresden.de
[2] Ostbayerische Technische Hochschule Regensburg, Innovation and Competence Centre for Production Logisticsand Factory Planning (IPF), 93025 Regensburg, Germany; frank.herrmann@oth-regensburg.de
* Correspondence: marco.trost@tu-dresden.de

Abstract: A large number of researchers have addressed social aspects in hierarchical production planning. This article responds to research gaps identified in our previous literature review. Accordingly, consideration of social aspects and the economic implications of social improvements are required in a longer term planning approach. For this, we integrate work intensity as employee utilization in a general mixed-integer programming model for master production scheduling. Following existing fatigue functions, we represent the relationship between work intensity and exhaustion through an employee-utilization-dependent exhaustion function. We account for the economic implications through exhaustion-dependent capacity load factors. We solve our model with a CPLEX standard solver and analyze a case study based on a realistic production system and numerical data. We demonstrate that the consideration of economic implications is necessary to evaluate social improvements. Otherwise, monetary disadvantages are overestimated, and social improvements are, thus, negatively affected. Moreover, from a certain level of work-intensity reduction, demand peaks are smoothed more by pre-production, which requires more core employees, while temporary employment is reduced. Further potential may arise from considering and quantifying other interdependencies, such as employee exhaustion and employee days off. In addition, the relationship between social working conditions and employee turnover can be integrated.

Keywords: capacity load; employee utilization; exhaustion; linear optimization; master production scheduling; social aspects

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1. Introduction

Insufficient consideration of social aspects causes increased physical and psychological exhaustion, as indicated by a decrease in employee productivity [1] and a lower level of employee satisfaction [2,3]. Research on social aspects is concerned with interactions of humans and other elements of a system in order to improve human well-being and system performance [4]. Thus, social aspects should be considered next to economic factors. In this regard, social aspects can be influenced by production planning and control (PPC) [5]. However, the social dimension is often neglected in PPC [6,7], while economic and environmental aspects have already been discussed widely (see, e.g., [8]). As implemented in commercially available enterprise resource planning systems, PPC consists of a hierarchy of: master production scheduling (MPS), material requirements planning and scheduling (as described in [9–11]). Thereby, e.g., employee well-being can be affected, especially in terms of work intensity, exhaustion and employee performance [5,12,13], since the concrete utilization and the workload of employees are determined by the assignment of employees to specific jobs. Further, the PPC is also affected by such employee-related social aspects and dependent employee productivity (e.g., processing times) and availability (e.g., due to illness).

Based on our previous literature review (see [7]), this article addresses identified research gaps regarding social improvements through PPC. We found that they are primarily included in the assembly line balancing problem (ALBP) and job rotation. In this context, social improvements in these short-term planning approaches can cause increased demand for production resources, for example, employees, cycle time and work stations [14–18]. However, short-term adjustments of these resources are limited or unfeasible. Therefore, a longer term planning approach is required to provide an adapted production program or production resources and the (dis)advantages of social improvements should be compared [7,18]. Such longer term planning decisions are currently rarely supported. Existing approaches only regard aspects of hiring and turnover as well as employee training. Furthermore, the specific employee-related social aspects are often regarded separately and possible synergies between different aspects are not observed. Primarily, within the approaches, the aim is to verify the suitability of the proposed solution method. Concrete social and economic correlations are discussed only rarely.

With our approach, we aim to contribute to close these gaps. Figure 1 illustrates the framework of this article regarding the identified gaps from the previous literature review.

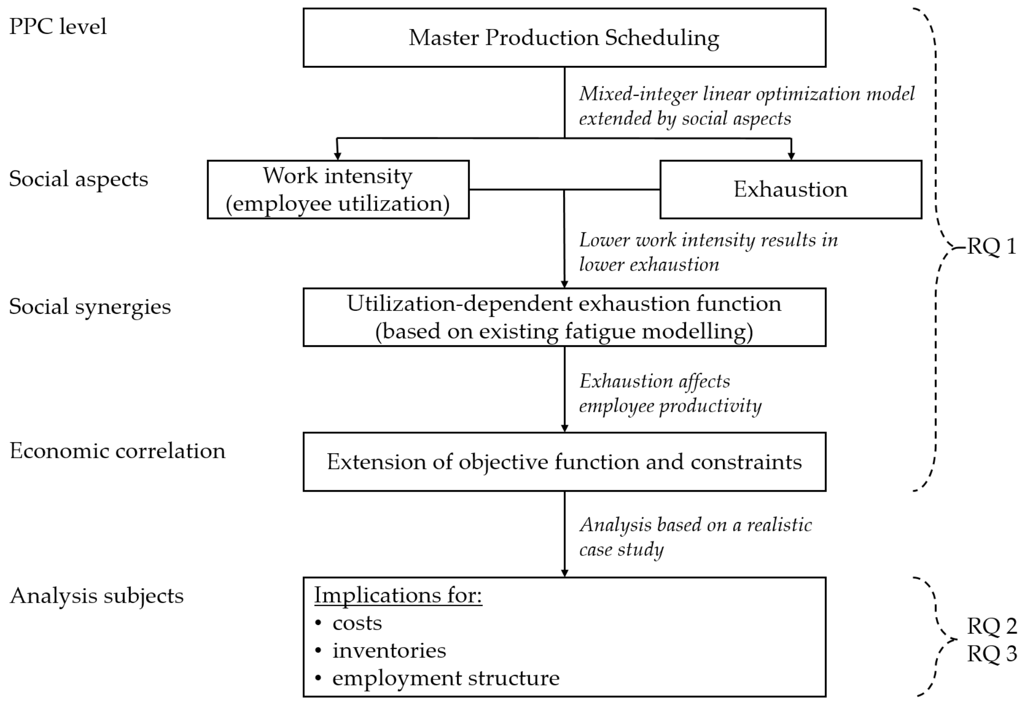

Figure 1. Research framework.

To meet the longer term planning required, we extend a general MPS by integrating employee-related social aspects. From the employees' point of view, especially work intensity is rated as insufficient [19–21]. For this, we represent work intensity with employee utilization. Further, synergies between work intensity and employee exhaustion are accounted for using a utilization-dependent exhaustion function based on existing fatigue models. In general, MPS implicitly includes exhaustion effects. However, the real exhaustion is usually either overestimated or underestimated. In our approach, a more precise (exhaustion-dependent) employee productivity is provided which is required to analyze the impact of social improvements. For the analysis, we examine different scenarios derived from a realistic case study of a company in the metal and electrical industry located in Germany and randomly generated data. Based on this, we answer the following research questions (RQ) in order to analyze the implications of social improvements.

RQ 1: How can the established description of exhaustion be integrated on an MPS level?
RQ 2: Which cost implications arise due to a reduction in work intensity (employee utilization)?

RQ 3: How will lower exhaustion due to lower work intensity (employee utilization) affect employment structure and pre-production?

For this, the article is structured as follows. Section 2 presents a literature review, which contains employee-related social aspects and the associated exhaustion-dependent performance deficits as well as the current state of the art. In Section 3, a general optimization model for MPS and the consideration of utilization-dependent exhaustion effects and subsequent capacity requirements are described. The test problem analyzed as well as our experimental design are presented in Section 4. The results and their discussion are outlined in Section 5. Finally, the article ends with a conclusion in Section 6.

2. Literature Review

2.1. Employee-Related Social Aspects

The social dimension is one of the pillars of sustainability, along with the economic and ecological dimensions [22]. In the past, different indicators and standards have been developed for reflecting sustainability [23]. In this regard, ref. for consisty with your adjustments below [24] analyze various sustainability indicators and categorize them. Employee-related social aspects are subdivided, thereby, into the areas of health and safety, development and satisfaction. A comparable differentiation can be found in the GRI (Global Reporting Index) standard [25]. From the standards contained therein, standards 401 (employment), 403 (occupational health and safety) and 404 (training and education) can be influenced by PPC [7]. Employee-related social aspects can consequently be subdivided into the four areas (occupational) health and safety, development (training and education), satisfaction, and employment, which are further subdivided, in ref. [7], on the foundation of existing approaches (see Figure 2). For a more comprehensive description, we refer to ref. [7].

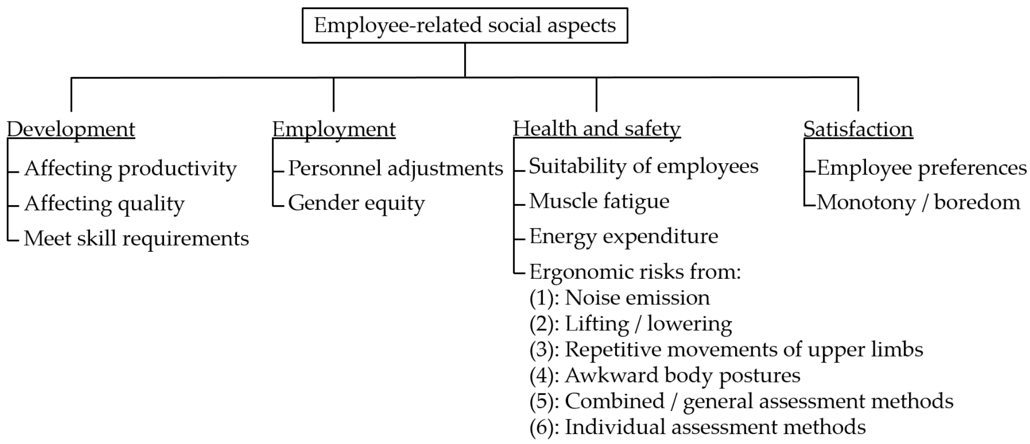

Figure 2. Categorization of employee-related social aspects [7].

An insufficient consideration of such employee-related social aspects leads, for example, to an increase in physical as well as mental exhaustion, and performance deficits due to this exhaustion can be observed [26]. Further, in the short-term, an increased heart rate, frustration and more aggressive behaviour can occur [27]. In the long-term, this leads to psychosomatic illnesses, increased time off work, resignation and demotivation [27], which is reflected in reduced efficiency and employee productivity [1,28]. Due to these effects, also, increased error rates [29,30] and lower employee satisfaction [3] occur. Reasons for these complaints contain work stress factors [31]. In this respect, from the perspective of the employees, especially the work intensity respectively the level of time/deadline pressure in performing tasks are rated as insufficient (as too high) [19–21] which causes, e.g., an increased exhaustion. In this context, both, deadline and time pressure as well as work intensity, are closely linked [21]. They can occur as a result of a scarce number of employees combined with a high workload. Thus, this relation reflects the extent to which capacity requirements are covered by available capacity. This relation we denote as the employee utilization.

2.2. Survey of Existing Approaches

Employee-related social aspects can be influenced by industrial companies through PPC [5]. Based on our previous literature review (see [7]), we found that different approaches already exist and are being applied for sub-problems of the PPC. Employee-related social aspects from all areas (see Figure 2) are included, thereby, at different levels of PPC. However, there is a significant prevalence of considering health and safety aspects at the ALBP and job rotation [7].

In existing approaches for ALBP, the aim is to distribute the tasks among the stations in such a way that health-and-safety risks per station are either minimized (see, e.g., [32,33]) or constrained (see, e.g., [34,35]). For job rotation, the aim is to assign employees to stations in such a way that ergonomic risks per employee are either minimized (see, e.g., [36,37]) or constrained (see, e.g., [36,38]). Within approaches for lot sizing, the aim is to exclude lot sizes if their ergonomic risks are too high (see, e.g., [39–41]). At these planning levels, approaches that also consider the associated effects of lower exhaustion (e.g., higher employee productivity) could not be identified. However, ref. [42] reports that improving social aspects can cause a need for additional production resources, at least from a certain level of social improvement. Thus, a decision-making problem arises regarding whether and how significantly employee-related social aspects can be improved. For this, ref. [18] recommends that financial factors should also be considered for possible required adjustments to the production program and corresponding production resources. This decision-making problem is assigned to a longer-term-oriented planning level. Regarding such planning problems, existing approaches address the employment and development of employees. In terms of improving employment aspects, the primary aim is to limit personnel adjustments by restricting the share of hiring and turnover relative to the number of employees [43–46]. Regarding the area of employee development, employee training is included. For this, training affects the productivity of employees [43,45,46] and production quality [44,47].

Hence, to the best of our knowledge, no approaches can be identified that provide an analysis of the (dis)advantages of improved employee-related social aspects. Especially, the following issues have not been addressed adequately so far.

- Employee-related social aspects have rarely been considered at plant level. In this aggregated perspective, longer term planning approaches have not addressed aspects of employee satisfaction and health and safety.
- An analysis of the relationship between social improvements and economic impact is rarely provided. The focus is mainly on the verification of the solution methods applied.

3. MPS with Utilization-Dependant Exhaustion and Subsequent Capacity Requirements

3.1. Optimization Model for MPS Including Employee-Related Social Aspects

We introduce the developed MPS optimization model in two steps, using the notation presented in Table 1. First, we include work intensity as an employee-related social aspect in a general MPS by means of a variable available capacity and employee-utilization control. Secondly, we describe our employee-utilization-dependent exhaustion model and derive the subsequent exhaustion-dependent capacity load (see Section 3.2).

Table 1. Notation.

Sets	
EG	Set of employee groups ($eg = 1, 2, ..., EG$)
J	Set of production segments ($j = 1, 2, ..., J$)
K	Set of products ($k = 1, 2, ..., K$)
S	Set of shift models ($s = 1, 2, ..., S$)
T	Set of time periods ($t = 0, 1, ..., T$)
Z	Set of lead-time periods for capacity load ($z = 0, 1, ..., Z$)
Parameters	
α_j	Parameter that controls the speed of exhaustion accumulation in production segment j
β_j	Parameter that controls the speed of exhaustion recovery in production segment j
$Capa_{eg}$	Available capacity per period and employee of an employee group eg
$d_{k,t}$	Demand per product k and period t
$f_{z,j,k}$, $SCLF_{z,j,k}$	Capacity load factor for lead-time period z, production segment j and product k
h_k	Inventory holding costs per unit and period of product k
I_k^{Init}	Initial inventory level per product k
I_k^{Max}	Maximum inventory level per product k
m_{eg}^{Cost}	Cost rate for hiring an employee from employee group eg
MP_j	Exhaustion-dependent portion of capacity load factors in production segment j
n_{eg}^{Cost}	Cost rate for employee turnover per employee from employee group eg
R_j^{Max}	Maximum permitted employee utilization in production segment j
$Shift_s$	Factor for calculating shift surcharges for using shift model s
$Shift_{j,s}^{Above}$	Maximum number of employees per production segment j in shift model s
$Shift_{j,s}^{Bottom}$	Minimum number of employees per production segment j in shift model s
$Staff_{eg,j}^{Cost}$	Cost rate per employee from employee group eg in production segment j
$Staff_{eg,j,s}^{Init}$	Initial number of employees from employee group eg in production segment j and shift model s
$Staff_{eg,j}^{Max}$	Maximum number of employees from employee group eg in production segment j
$Staff_{eg,j}^{Min}$	Minimum number of employees from employee group eg in production segment j
$Staff_j^{TotalMax}$	Maximum number of employees in production segment j
$Staff_j^{TotalMin}$	Minimum number of employees in production segment j
U_j^{Limit}	Minimum employee utilization in production segment j below which exhaustion not decrease
we_{eg}	Lead-time periods for hiring employees from employee group eg
wf_{eg}	Lead-time periods for employee turnover from employee group eg
Decision variables	
$a_{j,t}$	Available capacity per production segment j in period t
$b_{j,t}$	Capacity requirement per production segment j in period t
$E_j(U_j)$	Accumulated exhaustion at employee utilization U_j in production segment j
$EF_j(U_j)$	Exhaustion factor (normalized exhaustion level) in production segment j
$EL_j(U_j)$	Exhaustion level after exhaustion accumulation and exhaustion recovery in production segment j
$f_{z,j,k}(EF_j(U_j))$	Exhaustion-dependent capacity load factor for lead-time period z, production segment j and product k
$I_{k,t}$	Inventory level per product k in period t
$m_{eg,j,t}$	Number of hired employees from employee group eg in production segment j and period t
$n_{eg,j,t}$	Amount of employee turnover from employee group eg in production segment j and period t
$p_{j,s,t}$	Boolean variable for selection of the used shift model per production segment j, shift model s and period t
$Staff_{eg,j,s,t}$	Number of employees from employee group eg in production segment j, shift model s and period t
U_j	Employee utilization (work intensity) in production segment j
$x_{k,t}$	Production quantity per product k in period t

In general, the aim of MPS is to define decentralized production programs over several periods and to coordinate these production programs over all production segments of a production plant [48]. For this, MPS determines production quantities $x_{k,t}$ for a product k (with $1 \leq k \leq K$) per period t of a planning horizon T (with $1 \leq t \leq T$) to meet customer demand ($d_{k,t}$). The customer demands are based on existing orders and short-term forecasts. The products consist of various components and their production requires several periods. This leads to cumulative lead time (Z). Therefore, the production process causes capacity loads in the periods $t - z$ (with $0 \leq z \leq Z$). This is reflected via capacity load factors ($f_{z,j,k}$). Set-up times are not considered explicitly, thereby, since MPS considers 'extra big' time buckets at an aggregated level [9–11]. According to the production program and the capacity load factors, capacity requirements per production segment j (with $1 \leq j \leq J$) occur, which are balanced with the available capacity per production segment. This available capacity is generally composed of a fixed core available capacity and an unspecified variable use of additional capacity. Thus, deviations between available capacity and capacity requirements can be compensated by the use of these additional capacities or by production in advance. This results in a corresponding inventory level ($I_{k,t}$) or costs for the additional capacity. The objective is usually to minimize these costs for inventory holding and use of additional capacities.

In our approach, we extend this general model description, on the one hand, through a more detailed modeling of a variable available capacity. For this, for each production segment, employees can be hired and laid off, and different predefined shift models can be used. On the other hand, we integrate the work intensity as a relation between capacity requirement and available capacity. This relation we refer to as employee utilization. This adapted modeling provides the assurance of a preferred work intensity while customer demand is entirely satisfied (no backlogs). The consideration of the variable available core capacity also provides more flexibility to ensure the required work intensity. As a result, next to the production program, a corresponding personnel requirement is also determined, which is necessary to satisfy customer demand and ensure the required work intensity. The resulting optimization model is described next.

Objective Function

The objective is to minimize the total costs (Equation (1)). Next to the usually considered inventory holding costs, the costs of staffing, hiring and turnover as well as costs resulting from the shift model used are accounted for (Equations (2)–(7)). Thereby, costs of the available core capacity are included in these costs elements, as in our approach the available core capacity is variable.

$$ObjectiveFunction: \quad Minimize(TotalCosts) \tag{1}$$

$$\begin{aligned} TotalCosts = {} & InventoryCosts + StaffingCosts + ShiftCosts \\ & + HiringCosts + TurnoverCosts \end{aligned} \tag{2}$$

$$InventoryCosts = \sum_{t=1}^{T} \sum_{k=1}^{K} (h_{k,t} \cdot I_{k,t}) \tag{3}$$

$$StaffingCosts = \sum_{t=1}^{T} \sum_{s=1}^{S} \sum_{j=1}^{J} \sum_{eg=1}^{EG} (Staff^{Cost}_{eg,j} \cdot Staff_{eg,j,s,t}) \tag{4}$$

$$ShiftCosts = \sum_{t=1}^{T} \sum_{s=1}^{S} \sum_{j=1}^{J} \sum_{eg=1}^{EG} (Staff^{Cost}_{eg,j} \cdot Staff_{eg,j,s,t} \cdot Shift_s) \tag{5}$$

$$HiringCosts = \sum_{t=1}^{T} \sum_{j=1}^{J} \sum_{eg=1}^{EG} (m^{Cost}_{eg} \cdot m_{eg,j,t}) \tag{6}$$

$$TurnoverCosts = \sum_{t=1}^{T} \sum_{j=1}^{J} \sum_{eg=1}^{EG} (n^{Cost}_{eg} \cdot n_{eg,j,t}) \tag{7}$$

Constraints

In the constraints, we first adopt the inventory balance sheet (Equation (8)), the determination of the initial inventory level (Equation (9)), the limitation of the maximum inventory level (Equation (10)), and the determination of capacity requirements (Equation (11)) from general modeling (see, e.g., [11,48]).

$$d_{k,t} = x_{k,t} + I_{k,t-1} - I_{k,t} \qquad \forall 1 \le k \le K, \forall 1 \le t \le T \tag{8}$$
$$I_k^{Init} = I_{k,t=0} \qquad \forall 1 \le k \le K \tag{9}$$
$$I_k^{Max} \ge I_{k,t} \qquad \forall 1 \le k \le K, \forall 1 \le t \le T \tag{10}$$

$$b_{j,t} = \sum_{z=0}^{Z} \sum_{k=1}^{K} (f_{z,j,k} \cdot x_{k,t+z}) \qquad \forall 1 \le j \le J, \forall 1 \le t \le (T-Z) \tag{11}$$

We realize our extensions regarding the variable available capacity via Equations (12)–(18). With Equation (12), we determine the available capacity ($a_{j,t}$) based on the number of employees ($Staff_{eg,j,s,t}$) and the available capacity of one employee ($Capa_{eg}$). For this, hiring ($m_{eg,j,t-we_{eg}}$) and turnover ($n_{eg,j,t-wf_{eg}}$) are integrated using an employee balance sheet (Equation (13)) and the initial number of employees is defined (Equation (14)). Different employee groups (EG) reflect different employee skills, experiences, and employment conditions. This also enables a differentiation of the employees on the basis of their predispositions or individual characteristics. Legal restrictions are considered using lead times for employee turnover (wf_{eg}) and there are also lead times for hiring (we_{eg}). Additionally, bounds are set per production segment for the minimum number of employees (Equation (15)) and the maximum number of employees (Equation (16)). In Equation (17), the minimum number of employees per production segment and employee group ($Staff_{eg,j}^{Min}$) is limited in order to ensure an adequate availability of employees with appropriate skills and experiences. Further, the restriction of a maximum number of employees per production segment and employee group ($Staff_{eg,j}^{Max}$) represents the limitation on available skilled and experienced employees in the labor market (Equation (18)).

$$a_{j,t} = \sum_{eg=1}^{EG} \sum_{s=1}^{S} (Staff_{eg,j,s,t} \cdot Capa_{eg}) \qquad \forall 1 \le j \le J, \forall 1 \le t \le T \tag{12}$$

$$\sum_{s=1}^{S} Staff_{eg,j,s,t} = \sum_{s=1}^{S} (Staff_{eg,j,s,t-1} + m_{eg,j,t-we_{eg}} - n_{eg,j,t-wf_{eg}}) \qquad \forall 1 \le eg \le EG, \forall 1 \le j \le J, \forall 1 \le t \le T \tag{13}$$

$$Staff_{eg,j,s}^{Init} = Staff_{eg,j,s,t=0} \qquad \forall 1 \le eg \le EG, \forall 1 \le j \le J, \forall 1 \le s \le S \tag{14}$$

$$Staff_j^{TotalMin} \le \sum_{eg=1}^{EG} \sum_{s=1}^{S} Staff_{eg,j,s,t} \qquad \forall 1 \le j \le J, \forall 1 \le t \le T \tag{15}$$

$$Staff_j^{TotalMax} \ge \sum_{eg=1}^{EG} \sum_{s=1}^{S} Staff_{eg,j,s,t} \qquad \forall 1 \le j \le J, \forall 1 \le t \le T \tag{16}$$

$$Staff_{eg,j}^{Min} \le \sum_{s=1}^{S} Staff_{eg,j,s,t} \qquad \forall 1 \le eg \le EG, \forall 1 \le j \le J, \forall 1 \le t \le T \tag{17}$$

$$Staff_{eg,j}^{Max} \ge \sum_{s=1}^{S} Staff_{eg,j,s,t} \qquad \forall 1 \le eg \le EG, \forall 1 \le j \le J, \forall 1 \le t \le T \tag{18}$$

We control the work intensity using Equation (19). For this, the relation between capacity requirement ($b_{j,t}$) and available capacity ($a_{j,t}$) is limited to R_j^{Max}. This is the control parameter for the work intensity and represents the maximum permitted employee utilization. With this, a social improvement can be ensured. For example, with a conventionally considered employee utilization of 100% ($R_j^{Max} = 1.00$) and 6.0 assigned productive working hours per day, reducing the employee utilization to 80% ($R_j^{Max} = 0.80$) means that only 4.8 working hours are assigned to an employee per work day. The difference of 1.2 h is distributed over the entire working time; thus, the work intensity will be reduced.

$$b_{j,t} \leq R_j^{Max} \cdot a_{j,t} \qquad \forall 1 \leq j \leq J, \forall 1 \leq t \leq (T - Z) \tag{19}$$

Our last extension is to reflect the used shift model via Equations (20)–(22). The selection of the number of shifts per day is thereby determined according to the number of employees. To each shift model a lower ($S_{j,s}^{Bottom}$) (see Equation (20)) and an upper ($S_{j,s}^{Above}$) (see Equation (21)) limit of the number of employees are assigned and $p_{j,s,t}$ represents the selected shift model. Equation (22) ensures that only one shift model is active per production segment and planning period.

$$\sum_{eg=1}^{EG} Staff_{eg,j,s,t} \leq p_{j,s,t} \cdot S_{j,s}^{Above} \qquad \forall 1 \leq j \leq J, \forall 1 \leq s \leq S, \forall 1 \leq t \leq T \tag{20}$$

$$\sum_{eg=1}^{EG} Staff_{eg,j,s,t} \geq p_{j,s,t} \cdot S_{j,s}^{Bottom} \qquad \forall 1 \leq j \leq J, \forall 1 \leq s \leq S, \forall 1 \leq t \leq T \tag{21}$$

$$\sum_{s=1}^{S} p_{j,s,t} = 1 \qquad \forall 1 \leq j \leq J, \forall 1 \leq t \leq T \tag{22}$$

Finally, Equations (23) and (24) define the non-negative and binary conditions.

$$a_{j,t},\ b_{j,t},\ I_{k,t},\ m_{eg,j,t},\ n_{eg,j,t},\ Staff_{eg,j,s,t},\ x_{k,t} \geq 0 \qquad \forall eg, \forall j, \forall k, \forall s, \forall t \tag{23}$$

$$p_{j,s,t} \in \{0,1\} \qquad \forall j, \forall s, \forall t \tag{24}$$

3.2. Exhaustion Modeling

To reflect employee exhaustion aggregated to MPS, we adopt approaches to muscular fatigue. In this regard, the maximum endurance time (MET) is the length of time an employee can exert a specific effort before a capability limit is reached [49]. It is a function of the applied force which is a portion of the maximum voluntary contraction (MVC) of a muscle while performing a particular task [49]. However, MET models are limited in that they predict a fatigue endpoint at a given MVC load but do not provide an indication of the shape of the fatigue-accumulation function nor represent the fatigue state over the progress of task performance [28]. For this reason, ref. [28] proposed a function for quantifying fatigue accumulation for the lot sizing level (see Equation (25)). Further, they consider that production cycles are usually interrupted by recovery breaks, which contributes to a reduction in the previous accumulated fatigue (see Equation (26)).

$$F(t) = 1 - exp^{(-\gamma \cdot t)} \tag{25}$$

$$R(\tau_i) = F(t) \cdot exp^{(-\mu \cdot \tau_i)} \tag{26}$$

Thereby, $F(t)$ is the fatigue accumulated up to time t ($\leq MET$) and $R(\tau_i)$ is the residual fatigue after a rest of length τ_i. The parameters γ and μ control the speed of fatigue accumulation and recovery.

Transferred to the MPS level, it has to be taken into account that the regarded production program is realized by several employees, while the specific assignment of tasks to employees is not regarded at this planning level. Similarly, the specific number, duration, and timing of recovery breaks are not determined at the MPS level. Therefore, a different, more aggregated, representation is required for application at the MPS level. For this, we use the extent to which production output (capacity requirements) is covered by available capacity (see Equation (27)). This enables one to approximate the workload of the employees regardless of a detailed task and rest assignment and a longer term analysis of the (dis)advantages of social improvements can be provided. The aggregate fatigue determined in this way we refer to as exhaustion, since the aggregation also implicitly includes further aspects of employee exhaustion. In this context, the work intensity is also reflected, which we have already defined as employee utilization (relation between capacity requirement and available capacity).

$$U_j = \frac{\sum_{t=1}^{T} b_{j,t}}{\sum_{t=1}^{T} a_{j,t}} \qquad \forall 1 \leq j \leq J \qquad (27)$$

With lower employee utilization, there is a lower work intensity and a lower exhaustion accumulation (and vice versa). Similarly, the length of rest breaks increases with lower employee utilization. As a result, exhaustion recovery increases with lower employee utilization. In addition, we also consider that further aspects can have an exhaustive effect (e.g., monotony/boredom). Therefore, we model the reduction in exhaustion due to lower employee utilization only up to a certain limit of utilization reduction (U_j^{Limit}). Thus, as employee utilization is reduced to below this limit, the exhaustion does not decrease. We also assume that the break interval between two successive planning periods is sufficiently large so that no residual exhaustion has to be carried forward from one planning period to the next (for carrying forward a residual exhaustion/fatigue, see [28]). Hence, based on Equations (25) and (26) and the previous explanations, we derive the following functions to determine the utilization-dependent exhaustion level (see Equations (28) and (29)). Due to the different work requirements in the production segments, we regard the exhaustion as production-segment specific.

$$E_j(U_j) = 1 - exp^{(-\alpha_j \cdot U_j)} \qquad \forall 1 \leq j \leq J \qquad (28)$$

$$EL_j(U_j) = \begin{cases} E_j(U_j^{Limit}) \cdot exp^{(-\beta_j \cdot (1 - U_j^{Limit}))} & ;\text{for } 0 \leq U_j \leq U_j^{Limit} \\ E_j(U_j) \cdot exp^{(-\beta_j \cdot (1 - U_j))} & ;\text{for } U_j^{Limit} < U_j \leq 1 \end{cases} \qquad \forall 1 \leq j \leq J \qquad (29)$$

$E_j(U_j)$ represents the accumulated exhaustion due to an employee utilization U_j, where α_j controls the speed of the exhaustion increase. Accordingly, $EL_j(U_j)$ is the residual exhaustion due to the recovery from $1 - U_j$, where β_j controls the speed of the recovery. Furthermore, U_j^{Limit} defines the limit below a reduction in employee utilization will not, in addition, cause a reduction in exhaustion (e.g., due to monotony/boredom effects). Since we do not investigate employee utilization below this limit in this paper, we conveniently assume a constant exhaustion level. An example illustrating the utilization-dependent exhaustion level is provided by Figure 3.

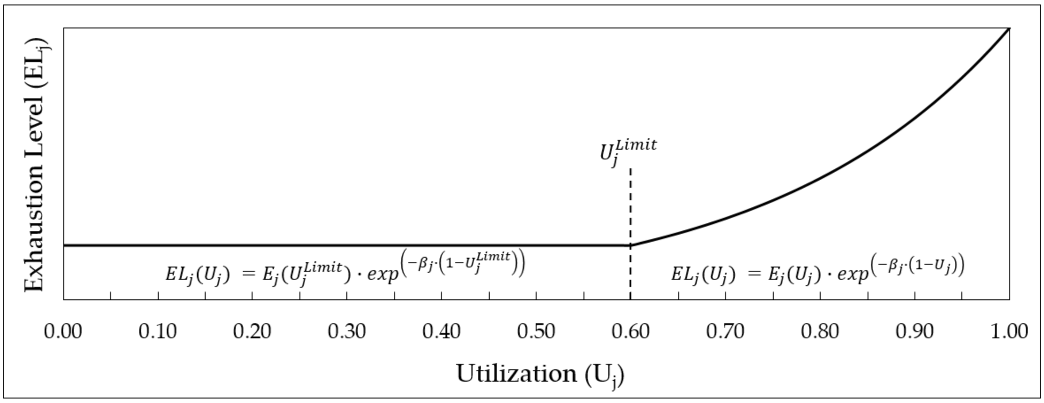

Figure 3. Exemplary function of a utilization-dependent exhaustion level.

In the concluding step, we account for the exhaustion-related performance losses (see, e.g., [26]). For this purpose, we model an exhaustion-dependent capacity load factor ($f_{z,j,k}(EF_j(U_j))$). For distinction, we denote the previous capacity load factor (see Section 3.1) as the standard-capacity load factor ($SCLF_{z,j,k}$). The new capacity load factors consist of an exhaustion-dependent portion (MP_j) and a non-exhaustion-dependent portion ($1 - MP_j$). With an employee utilization of 1.00 (100%), the new capacity load factor is as high as the standard-capacity load factor ($f_{z,j,k}(EF_j(U_j = 1.00)) = SCLF_{z,j,k}$). For this, we follow two steps. First, we form a utilization-dependent exhaustion factor ($EF_j(U_j)$) as the normalized utilization-dependent exhaustion level ($EL_j(U_j)$) related to the maximum exhaustion level ($EL_j(U_j = 1.00)$). Second, the new capacity load factor is determined based on this exhaustion factor, the previous standard-capacity load factor and the exhaustion-dependent portion. Thus, the exhaustion-dependent part of the standard-capacity load factor will decrease with decreasing employee utilization to the equivalent extent that the utilization-dependent exhaustion level decreases (see Equations (30) and (31)). With this, we link the social and economic dimension, which enables us to analyze social improvements from a monetary perspective considering the benefits of social improvements.

$$EF_j(U_j) = \frac{EL_j(U_j)}{EL_j(U_j = 1.00)} \qquad \forall 1 \le j \le J \tag{30}$$

$$f_{z,j,k}(EF_j(U_j)) = SCLF_{z,j,k} \cdot MP_j \cdot EF_j(U_j) + SCLF_{z,j,k} \cdot (1 - MP_j) \qquad \forall 1 \le j \le J \tag{31}$$

Considering the exhaustion-dependent capacity load factor in the previously formulated optimization model (see Section 3.1) would lead to a non-linearity due to the multiplication with the production quantity ($x_{k,t}$) (see Equation (11)), similar to the consideration of learning effects (see, e.g., [50,51]). For more applicability of this approach in industrial practice, we still consider the exhaustion-dependent capacity load factor as a parameter. Thus, we avoid the non-linearity. In this regard, it should be noted that with constant capacity load factors, the average employee utilization in the planning horizon approximates the maximum permitted employee utilization (R_j^{Max}) (see, e.g., [52–54]). Therefore, we determine the exhaustion-dependent capacity load factor based on this maximum permitted employee utilization and analyze different specifications of this parameter. The concrete values are given in Section 4.

4. Test Problem and Experimental Design

To analyze effects caused by work intensity, we consider randomly generated data and data based on a realistic production system from the metal and electrical industry located in Germany. For good readability and clarity for the reader, this case study is rather small. However, the results might not be dependent on the specific problem instance. The company produces welded assemblies for plant engineering, pipeline construction and the railway industry. Especially, the assembly process has a low level of automation and, due to regional factors, the company is affected by an ageing of the working population. Therefore, consideration of employee-related social aspects is highly relevant regarding the retention of skilled workers in the company and maintenance of a high level of performance. The structure of our experimental design is presented in Figure 4.

Regarding the parameter setting, for simplicity, we consider the production segment with a low level of automation ($J = 1$): the assembly production; and we consider two products ($K = 2$). Further, the lead time for products as well as hiring and turnover are zero ($Z = 0$, $we_{eg} = 0$, $wf_{eg} = 0$). The inventory holding costs are 65 money units (MU) per period and quantity unit (QU) for product one ($h_{k=1} = 65$) and 55 $MU \cdot (period \cdot QU)^{-1}$ for product two ($h_{k=2} = 55$) and the initial inventory level is zero for both products ($I_k^{Init} = 0$). Customer demands vary at different intensities around a mean value and have to be met at the beginning of a planning period. The mean values per planning period are 40,000 QU for product one ($k = 1$) and 50,000 QU for product two ($k = 2$). In order to map the varying demand we use randomly generated demand series, following a normal distribution and a coefficient of variation of 5%. Additionally, due to the storage capacity, a maximum inventory level of 40,000 QU for product one ($I_{k=1}^{Max} = 40{,}000$) and of 50,000 QU for product two ($I_{k=2}^{Max} = 50,000$) is feasible.

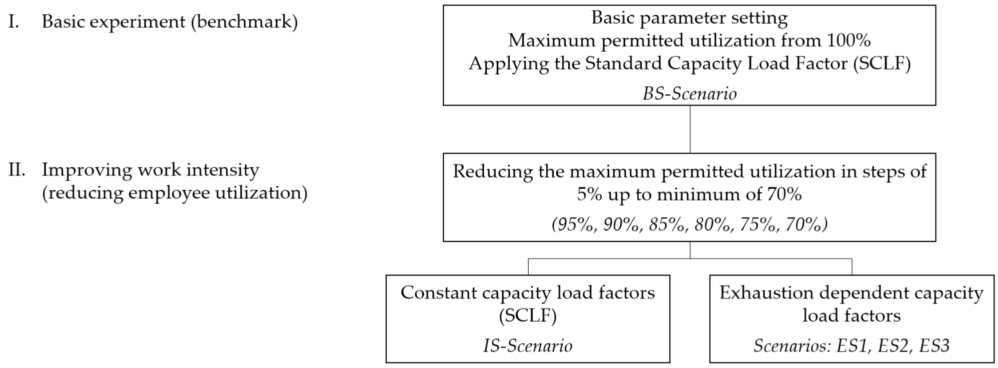

Figure 4. Structure of the experimental design.

The production is performed with employees, while, due to the low degree of automation, each station needs one employee exclusively when it is working. For this, we distinguish two employee groups ($EG = 2$), which represent core employees (employee group one ($eg = 1$)) and temporary employees (employee group two ($eg = 2$)). The experience gap between core and temporary employees we map via a lower monthly available capacity per employee ($Capa_{eg}$, approx. 17.5 days per month with 6.5 h per day—excluding vacation days, sick leave and unproductive working time). Further, different costs for hiring (m_{eg}^{Cost}), turnover (n_{eg}^{Cost}) and staffing ($Staff_{eg,j}^{Cost}$) occur due to the contracting of an employment agency for the employment of the temporary employees. The staffing costs for one employee per period are taken from the IG Metall labor agreement for metal and electrical industries, Saxony (Germany) from salary group five (additional level) [55], while 21.5% employer contribution is included as well. For the temporary employees, the staffing costs are higher, due to the agency service fees of 88%. The concrete values are given in Table 2.

Table 2. Parameters for core and temporary employees (abbr.: Money Units).

Employee Group (EG)	$\mathbf{Capa_{eg}}$ [in seconds]	$\mathbf{Staff_{eg,j=1}^{Cost}}$ [in MU]	$\mathbf{m_{eg}^{Cost}}$ [in MU]	$\mathbf{n_{eg}^{Cost}}$ [in MU]
$eg = 1$	405,000	3671	15,000	40,000
$eg = 2$	300,000	5692	1500	100

For both employee groups, the maximum available number of employees on the labor market is 6000 ($Staff_{eg,j=1}^{Max} = 6000$), while the initial and minimum number of employees is zero ($Staff_{eg,j=1,s}^{Init} = 0$, $Staff_{eg,j=1}^{Min} = 0$, $Staff_{j=1}^{TotalMin} = 0$). The number of employees per period determines the shift model S ($s = 1$ to $s = 3$ shifts) shown in Table 3. For this, 2000 workplaces are available per shift. Thus, with a three-shift system, a maximum of 6000 employees can be employed ($Staff_{j=1}^{TotalMax} = 6000$). The shift surcharges are taken from the IG Metall labor agreement for metal and electrical industries, Saxony (Germany) [56].

Table 3. Allowed shift models.

Shift Model (S)	$\mathbf{Shift_{j=1,s}^{Bottom}}$	$\mathbf{Shift_{j=1,s}^{Above}}$	$\mathbf{Shift_s}$
$s = 1$	0	2000	0.00%
$s = 2$	2001	4000	0.00%
$s = 3$	4001	6000	8.33%

The remaining parameters are specific to our experiments. In the following, we explain the specific settings of the experimental design (cf. Figure 4). Since the performance deficits due to insufficient employee-related social aspects, which are considered here, occur particularly in the case of continuous overload, long-term effects are investigated. Therefore, a planning horizon of 84 periods ($T = 84$) is considered, where one period corresponds to one month, and 12 periods are considered as warm-up as well as run-out phases. Thus, the results from 60 periods (5 years) are analyzed ($\hat{T} = 60$).

For the basic setting (BS), which is used as the benchmark scenario, we regard a conventional model setting in which employee utilization is not constrained and a constant, exhaustion-independent capacity load factor is applied. Thus, the maximum permitted employee utilization (work intensity) is not restricted ($R_{j=1}^{Max} = 1.00$). Further, as capacity load factors, the standard-capacity load factors ($SCLF_{z,j,k}$) are applied. These are 14,000 s per QU for product one ($SCLF_{z=0,j=1,k=1} = 14,000$) and 11,000 s per QU for product two ($SCLF_{z=0,j=1,k=2} = 11,000$). This means that a core employee can produce approx. 1.7 QU of product one or 2.1 QU of product two per shift.

Next, we compare the results of the BS scenario with the results of a stepwise improvement in the employee utilization (work intensity). For this, we reduce the maximum permitted employee utilization from the BS scenario in steps of 0.05 (5%) up to an employee-utilization level of 0.70 (70%). Regarding the applied capacity load factors, we define different scenarios with constant capacity load factors and exhaustion-dependent capacity load factors.

- Constant capacity load factors are applied within the IS scenario. Thereby, for each maximum permitted employee utilization the capacity load factors are equal to the standard-capacity load factors from the BS scenario ($f_{z,j,k}(EF_j(U_j = R_j^{Max})) = SCLF_{z,j,k}$). Thus, the benefits of improved work intensity and less exhaustion are not accounted for. With this, we aim to demonstrate the necessity of the more precise (exhaustion-dependent) modelling of employee productivity, like in this approach.
- By applying the exhaustion-dependent capacity load factors, we will account for increasing employee productivity due to reduced exhaustion. For this, in Equation (31), the exhaustion-dependent portion is 75% ($MP_{j=1} = 0.75$) which reflects the low level of automation in our case study. Since there are no empirical data for quantifying the exhaustion function so far, we compare three different exhaustion curves (ES1, ES2, ES3). Thereby, we are oriented by the work of ref. [57], who observed a decrease in maximum muscle strength of over 40% in a short-term push test. Due to the low level of automation in our case study, a similar correlation is expected as well. However, we also consider lower correlations. In this respect, we consider the following slow and fast speeds of exhaustion accumulation and exhaustion recovery while the exhaustion level can be reduced up to an employee utilization of 70% ($U^{Limit} = 0.70$).

  ES1: $\alpha = 6.00$, $\beta = 1.00$
  ES2: $\alpha = 3.00$, $\beta = 1.00$
  ES3: $\alpha = 6.00$, $\beta = 1.50$

  For each scenario, the resulting capacity load factors (from Equation (31)) as well as the respective exhaustion factors (from Equation (30)) are given in Table 4. The exhaustion factor reflects the extent to which the exhaustion level is reduced due to the reduced employee utilization. For example, an exhaustion factor of 0.84 means that the exhaustion level is reduced by 16% (compared to the exhaustion level at 100% employee utilization).

From these scenarios (BS, IS, ES1, ES2, ES3) and the maximum permitted employee-utilization values (100%, 95%, 90%, 85%, 80%, 75%, 70%), 25 individual planning problems occur for each demand series. We realize, thereby, 20 individual demand series. To indicate statistical significance, for the total costs, we calculate confidence intervals with bounds CI^- and CI^+ with an error probability of $1 - \alpha = 0.95$ and a normal distribution. With this, we calculate (for good readability) a relative deviation from the confidence interval bounds compared to the mean value ($CI^{relative}$). Each of these 500 individual planning problems was solved with CPLEX from IBM-ILOG version 12.7.1 on a PC with a processor of 2.50 GHz and 256 GB of RAM.

Table 4. Capacity load factors and exhaustion factors for exhaustion function 1 to 3 (scenarios ES1, ES2, ES3).

Utilization ($R_{j=1}^{Max}$)	Product (K)	$\mathbf{EF_{j=1}^{ES1}}$	$\mathbf{EF_{j=1}^{ES2}}$	$\mathbf{EF_{j=1}^{ES3}}$	$\mathbf{f_{z=0,j=1,k}^{ES1}}$ [in seconds]	$\mathbf{f_{z=0,j=1,k}^{ES2}}$ [in seconds]	$\mathbf{f_{z=0,j=1,k}^{ES3}}$ [in seconds]
95%	$k = 1$	0.95	0.94	0.93	13,479	13,403	13,233
	$k = 2$				10,591	10,531	10,397
90%	$k = 1$	0.90	0.89	0.86	12,981	12,827	12,519
	$k = 2$				10,200	10,078	9 836
85%	$k = 1$	0.86	0.84	0.80	12,505	12,268	11,854
	$k = 2$				9825	9639	9 314
80%	$k = 1$	0.81	0.78	0.74	12,047	11,726	11,234
	$k = 2$				9466	9214	8827
75%	$k = 1$	0.77	0.73	0.68	11,607	11,199	10,654
	$k = 2$				9120	8799	8371
70%	$k = 1$	0.73	0.68	0.63	11,181	10,684	10,111
	$k = 2$				8785	8394	7944

5. Results and Discussion

5.1. Cost Implications (RQ2)

The 500 individual planning problems could be solved optimally, with a runtime of a few seconds. The relative deviation from the confidence interval bounds compared to the mean value ($CI^{relative}$) was less than 0.42% for the total costs in all experiments. Thus, runtimes and confidence intervals are small and, therefore, they are not listed. However, the values for $CI^{relative}$ show that the results are statistically significant.

First, we regard the costs as well as the work intensity in order to analyze the implications of social improvements. For this, the total costs and the cost deviations, as well as the average employee utilization (work intensity) are presented in Table 5. Regarding the average employee utilization, it emerges that it converges to the maximum permitted employee utilization (R_j^{Max}). This demonstrates that our approach to modeling exhaustion using R_j^{Max} is appropriate. The impact of the applied exhaustion function (scenario IS, ES1, ES2, ES3) on the average employee utilization is marginal.

Table 5. Average employee utilization and total costs for each scenario (BS, IS, ES1, ES2, ES3).

Variable	Scenario	Maximum Permitted Employee Utilization ($R_{j=1}^{Max}$)						
		100%	**95%**	**90%**	**85%**	**80%**	**75%**	**70%**
Average employee utilization	BS	99.33%						
	IS		94.38%	89.42%	84.46%	79.52%	74.56%	69.56%
	ES1		94.36%	89.41%	84.45%	79.48%	74.52%	69.56%
	ES2		94.36%	89.40%	84.44%	79.48%	74.51%	69.55%
	ES3		94.36%	89.39%	84.42%	79.46%	74.50%	69.54%
Total costs	BS	616,564,291						
	IS		+5.22%	+11.01%	+17.49%	+ 24.78%	+33.03%	+42.57%
	ES1		+1.34%	+3.00%	+5.04%	+7.50%	+10.45%	+13.97%
	ES2		+0.77%	+1.78%	+3.07%	+4.66%	+6.60%	+8.94%
	ES3		−0.50%	−0.64%	−0.39%	+0.30%	+1.46%	+3.15%

By including the utilization-dependent exhaustion and the related exhaustion-dependent capacity load factors (such as in scenarios ES1, ES2, ES3), a more precise (exhaustion-dependent) employee productivity is provided than in conventional approaches. The significantly higher cost increases in the IS scenario indicate that modeling the socioeconomic interactions (exhaustion-dependent capacity load factors) are essential when departing from the usual aim of maximizing employee utilization. Without the consideration of the exhaustion effects (such as in scenario IS), in the case of exhaustive tasks, the monetary effects of reducing employee utilization (work intensity) would be significantly overestimated. Thus, a more precise consideration of exhaustion (such as in scenarios ES1, ES2, ES3) is required.

The reduction in employee utilization typically causes an increase in total costs. This explains why the aim, typically, is to maximize utilization. However, maximizing employee utilization is not cost-optimal in all situations, as demonstrated in scenario ES3 for a maximum permitted employee utilization of 95%, 90% and 85%. In this scenario, the lowest total costs occur at a maximum permitted employee utilization of 90%. This means that the average assigned production hours per employee and day can be reduced from 6.5 h ($R_j^{Max} = 1.00$) to 5.8 h ($R_j^{Max} = 0.90$), which also results in 0.64% lower costs. This demonstrates the possible positive correlation between social improvement and economic optimum. Furthermore, social improvements can also be achieved in the other scenarios (ES1 and ES2), whereby the expected percentage increase in costs is significantly lower than the percentage improvement in work intensity (respectively, in employee utilization and exhaustion level).

Additionally, the speed of exhaustion accumulation and recovery have opposite effects. Thus, a lower cost increase occurs with a lower speed of exhaustion accumulation (compare scenarios ES1: $\alpha = 6.00$ vs. ES2: $\alpha = 3.00$), respectively, with a higher speed of exhaustion recovery (compare scenarios ES1: $\beta = 1.00$ vs. ES3: $\beta = 1.50$). Further, increasing the speed of exhaustion reduction has a stronger impact than reducing the speed of exhaustion accumulation (compare scenarios ES2 vs. ES3). Thus, this indicates that measures to increase the speed of exhaustion recovery, e.g., through health programs, have a greater impact than comparable measures for reducing the speed of exhaustion accumulation.

Next to these effects, the amount of cost increases was not expected in this way. It should be noted that the identical production output has to be realized independently of the permitted maximum employee utilization. Therefore, a correspondingly higher available capacity is required to balance the reduced employee utilization. Especially for the scenario IS (without exhaustion consideration), it could be expected that the costs increase proportionately to the reduction in employee utilization, i.e., a reduction in the permitted maximum employee utilization by 20% causes a cost increase by approx. 20%. To understand how the deviations in the expected cost implications occur, in the following section we regard the effects of reducing work intensity on the employment structure and pre-production.

5.2. Implications for Employment Structure and Pre-Production (RQ3)

The main cause of the cost increase resulting from the reduction in work intensity is the change in personnel requirements. This is especially indicated by the increase in the average number of core employees ($eg = 1$). Due to the reduced employee utilization, additional employees are needed to realize the required output (see Table 6). When the exhaustion-dependent capacity load factors are not accounted for (IS scenario), the increase in required core employees can be approximated by the reciprocal value of the reduction in employee utilization. This correlation also occurs in further scenarios (ES1, ES2, ES3). However, since the exhaustion-dependent capacity load factors are applied in these scenarios, the fact that the capacity load also changes has to be taken into account. Thus, the occurring change in the number of core employees can be approximated using Equation (32) (see Table 6). It can be observed, thereby, that in scenario ES3 with a maximum permitted employee utilization of 95%, 90% and 85%, fewer core employees are required even though employee utilization is reduced. The reason for this is that in these situations, the exhaustion-dependent capacity load factors are reduced more than the required employee utilization.

$$\frac{StaffingCosts_{eg=1}(R_2^{Max})}{StaffingCosts_{eg=1}(R_1^{Max})} - 1 \approx \frac{R_1^{Max}}{R_2^{Max}} \cdot \frac{f_{z,j,k}(R_2^{Max})}{f_{z,j,k}(R_1^{Max})} - 1 \tag{32}$$

Table 6. Average number, percentage changes and expected changes (from Equation (32)) of core employees ($eg = 1$).

Variable	Scenario	Maximum Permitted Utilization ($R_{j=1}^{Max}$)						
		100%	95%	90%	85%	80%	75%	70%
Average number of core employees	BS	2748						
	IS		+5.25%	+11.09%	+17.63%	+24.96%	+33.28%	+43.07%
	ES1		+1.35%	+3.01%	+5.07%	+7.55%	+10.52%	+14.06%
	ES2		+0.78%	+1.80%	+3.08%	+4.68%	+6.64%	+8.99%
	ES3		−0.50%	−0.64%	−0.38%	+0.30%	+1.47%	+3.16%
Expected change	IS		+5.26%	+11.11%	+17.65%	+25.00%	+33.33%	+42.86%
	ES1		+1.35%	+3.03%	+5.08%	+7.56%	+10.54%	+14.09%
	ES2		+0.78%	+1.80%	+3.10%	+4.70%	+6.66%	+9.02%
	ES3		− 0.50%	−0.64%	−0.39%	+0.30%	+1.47%	+3.17%

Due to the low degree of automation, the staffing costs of the core employees are the major cost driver in this case study. Therefore, the described correlations are the main reason for the occurring cost implications. However, the change in total costs (see Table 5) is less than the expected change from Equation (32) (see Table 6). Even the deviations are small, this indicates that next to the change in core employees, further effects occur. The reason for the deviations is a change in the behavior concerning the compensation of varying capacity demand. In general, varying demand can be met by hiring temporary employees or by pre-production. As already mentioned, the same production output always has to be realized. Thus, the same level of pre-production could also be expected. However, as indicated by Figure 5, the level of pre-production changes in certain situations.

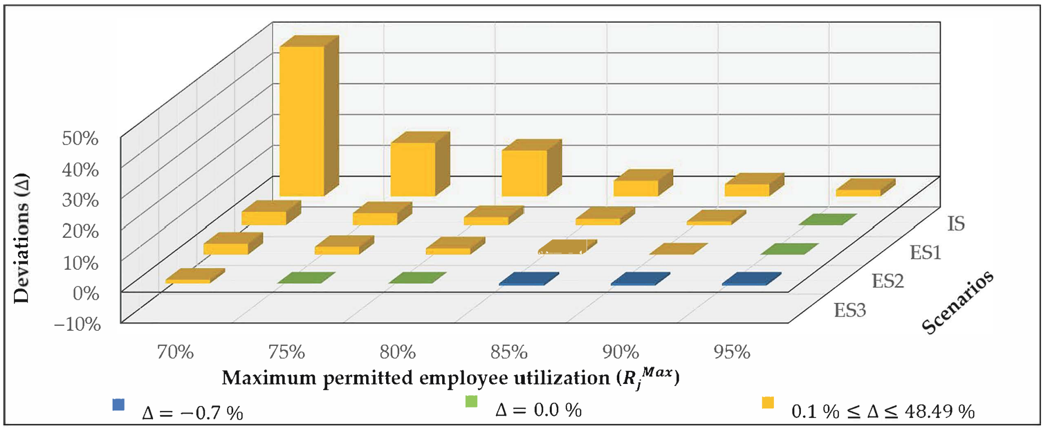

Figure 5. Deviations in the average inventory level related to the BS scenario.

First, the occuring deviations in pre-production are caused by an increase in the number of periods for which an adjustment of the core employees to compensate for a longer term varying-capacity-demand trend is more cost-efficient than a compensation by temporary employees (see Figure 6). It emerges that these changes in the number of periods correspond to the changes in pre-production (compare Figures 5 and 6). A reduced number of periods means that the adjustment of core employees is less advantageous than the use of temporary employees. Further, since for the pre-production available capacities of core employees are used, the reduced advantageousness of adjusting core employees causes a lower pre-production. In the opposite case, an increase in the number of periods causes a higher pre-production and a lower use of temporary employees.

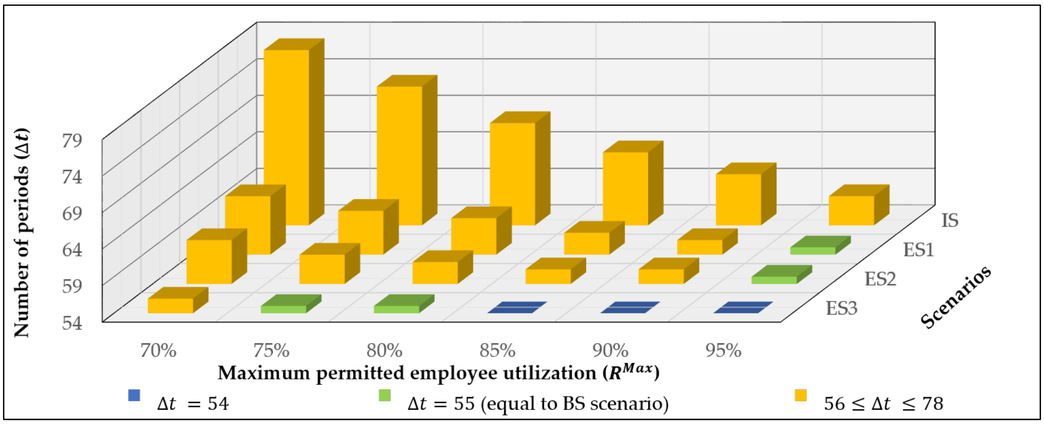

Figure 6. Number of periods for which an adjustment of core employees to compensate for varying demand is more cost-efficient than compensation by temporary employees.

Accordingly, the use of temporary employees is also affected. The relative change in the number of temporary employees initially follows the same relationships as the change in core employees described above and can be approximated by Equation (32) (see Table 6: "Expected change"). Furthermore, the changed number of periods for which an adjustment in core employees is more cost-efficient causes an overlapping effect. Thus, in scenario ES3 with a maximum permitted employee utilization of 95%, 90% and 85%, initially a lower number of temporary employees is expected. However, due to the changed number of periods for which an adjustment in the core employees is more cost-efficient, the number of temporary employees is not reduced by as much as would be expected (see Figure 7). This indicates that, as described above, the use of temporary workers is relatively higher. In contrast, a corresponding increase in temporary employees can be expected in the further scenarios (via Equation (32)). However, if the number of periods increases for which an adjustment in the core employees is more cost-efficient (see Figure 6), the increase in the number of temporary employees is less than would be expected (see Figure 7). Thus, the relative use of temporary workers is lower.

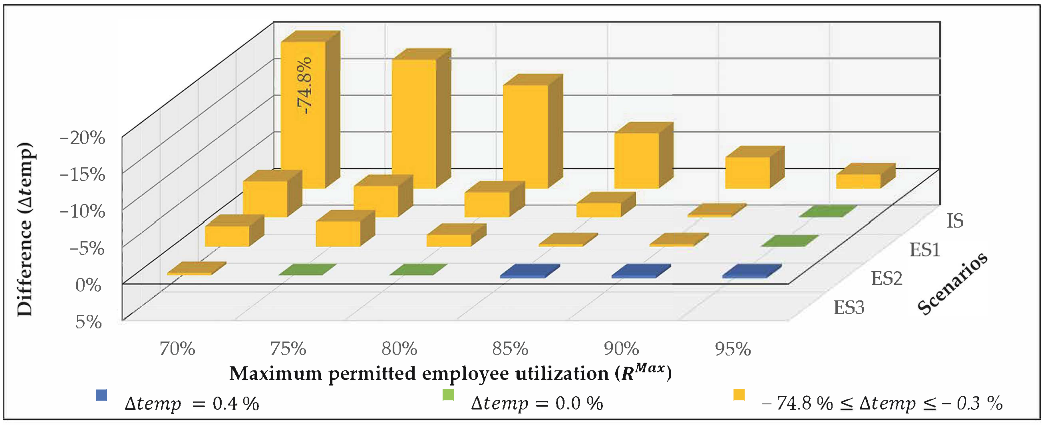

Figure 7. Difference between occuring and expected relative change in the average number of temporary employees ($eg = 2$).

This decision problem regarding the use of core employees or temporary employees generally arises when it is necessary to meet longer term demand trends. In contrast, for shorter term demand peaks, there is a second decision problem of whether the occurring capacity demand peaks should rather be compensated by the use of temporary employees or by pre-production. Thereby, the reduction in employee utilization changes the number of periods up to which pre-production is more beneficial than the use of temporary employees (see Figure 8). This increase, which occurs in scenario IS at a maximum permitted employee utilization of 80%, 75% and 70%, increases the advantageousness of pre-production compared to the use of temporary employees. It is reflected, on the one hand, in a higher average inventory level (see Figure 5) and, on the other hand, in a significantly smaller increase in the average number of temporary employees than expected (see Figure 7).

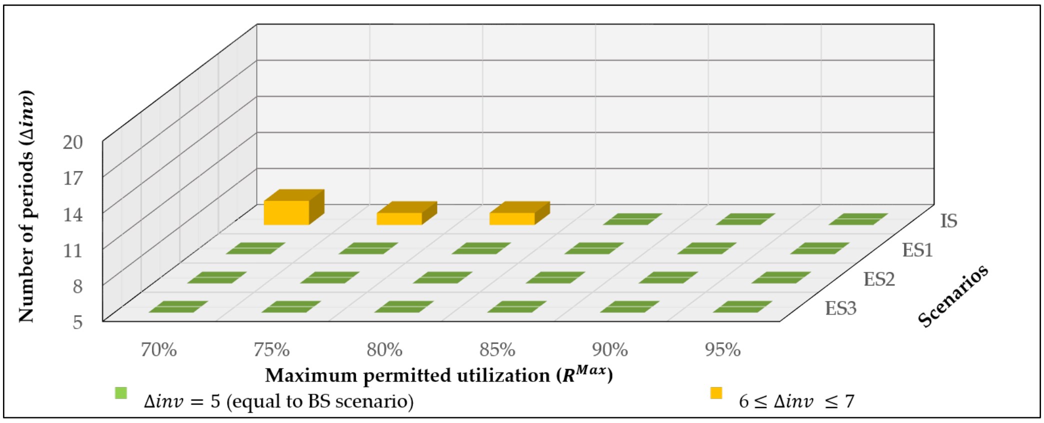

Figure 8. Number of periods in which pre-production is more economical than employing temporary employees ($eg = 2$).

Finally, it should be noted that in the IS scenario with a maximum permitted employee utilization of 70%, the described effects are significantly higher than in the further situations. Thus, the number of core employees increases much more than expected, the number of temporary employees is even reduced and the pre-production significantly increases. The reason for this is that, due to the reduced employee utilization, in some periods the total number of employees increases to such an extent that a shift model change occurs (a third shift is required). It should be noted that the core employees have higher productivity due to them being more experienced. We have mapped this via the parameter $Capa_{eg}$. Therefore, in order to reduce the shift costs, the total number of employees can be reduced by using more core employees instead of temporary employees. However, due to the high costs of the hiring and turnover of core employees, they are employed for a longer period of time. As a result, capacity demand peaks are smoothed out more to prior periods, which causes an additional increase in pre-production.

In summary, improving work intensity through lower employee utilization results in structurally different production programs and personnel requirements. Accordingly, it should be ensured that, for example, higher inventory levels are technically possible. Similarly, adapted personnel requirements imply an appropriate number of employees available on the labor market. This also supports the need to consider the reduction in work intensity over a long-term planning horizon, which permits adequate lead times to qualify or acquire the required experienced employees. With the presented optimization model, the occurring effects can be identified as well as analyzed, and suitable production programs and personnel requirements can be defined. However, we also demonstrated that maximizing employee utilization is not cost-optimal in all situations.

6. Conclusions

In this article, we demonstrate how reduced work intensity can be achieved using MPS and how this affects the production program and the employment structure. In previous approaches, primarily health and safety aspects on the levels of ALBP and job rotation are considered. Less attention is paid to multiple social aspects as well as to modeling of the resulting economic interactions. Existing research also suggested that longer term planning approaches are required to evaluate the (dis)advantages between social improvements and monetary tradeoffs. With the presented optimization model and the consideration of utilization-dependent exhaustion and exhaustion-dependent capacity load factors, such an approach is presented (RQ1).

We analyzed the impact of reduced work intensity in terms of costs, the required employee structure and the production program. In addition, we also analyzed the impact of different exhaustion functions. We found that improving work intensity (reduced employee utilization) requires the consideration of related exhaustion effects (higher employee productivity). Otherwise, monetary disadvantages are significantly overweighted (RQ2) and social improvements are disadvantaged. Whether, in addition to a social improvement, the regarded costs also decrease depends on the occuring impact of exhaustion on the capacity load factors (on employee productivity). Furthermore, measures to increase the speed of recovery were found to be more impactful than comparable measures to reduce exhaustion accumulation.

The observed cost implications are especially caused by an adapted employment of core employees, which can be aproximated via Equation (32). With this approximation, temporary employment can also be predicted. However, it has been found that the favorability between the employment of core employees and temporary employment as well as between the pre-production and the temporary employment can change from a certain reduction in employee utilization depending on the exhaustion function applied. This causes, especially, an adapted pre-production and an adaption of temporary employment (in addition to the expected adjustment from Equation (32)), while the average number of core employees is only marginally affected (RQ3). In this respect, the presented optimization model enables the quantification and analysis of such effects.

Finally, some limitations should also be mentioned. For example, further analysis in the field of ergonomics are required regarding the correlation of exhaustion and capacity load factors. In addition, it should be noted that improving employee-related social aspects has further effects that have not yet been integrated. For example, employee days off due to illness can be reduced. Further, different settings regarding the automation level and fluctuations in demand can be investigated. However, it could be demonstrated that the introduced optimization model enables the investigation of such questions.

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