INFLUENCE OF COMPANY SIZES IN ADAPTED MASTER PRODUCTION SCHEDULING FOR IMPROVING HUMAN WORKING CONDITIONS

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KEYWORDS

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ABSTRACT

Sustainability is an important topic in production planning and control. This article contributes in particular to further research on the social dimension. It presents a linear optimisation model for Master Production Scheduling in order to improve human working conditions. Existing approaches have already identified a considerable potential for improvements. Furthermore, this article analyses the influence of the company size on workload and costs using an application with a high proportion of manual activities. It is demonstrated that human working conditions can be improved independently from the company size without increasing costs. In addition, smaller companies tend to have a higher exhaustion and the workload affects the total costs more in smaller companies. Therefore, smaller companies might benefit more from an improvement in human working conditions.

INTRODUCTION

Sustainability is of rising relevance in research and practice, for example, due to various interest groups and other factors like resource shortages or a shortage of skilled workers. Production Planning and Control (PPC) enables corresponding improvements, since, for example, resources can be used more efficiently through an adapted planning approach. The PPC consists of a hierarchy of three levels: Master Production Scheduling (MPS), Material Requirements Planning and Scheduling; as introduced, for example, by Hax and Meal (1975) and Drexl et al (1994). However, existing approaches to sustainability focus on ecological aspects (see e.g. Grosse et al., 2017; Trost et al., 2019b). Therefore, we consider the integration of social aspects (i.e. exhaustion) in this paper.
Due to exhaustion, performance deficits occur in the case of a high proportion of manual activities, for example, through higher error rates (Neumann and Dul, 2010). We found out that exhaustion effects have so far been integrated at the level of lot sizing and scheduling. At the MPS level, only the work of Trost et al (2019a) is known, who identified a high potential for improved human working conditions through an adapted MPS.
In our paper, we extend this approach by considering different company sizes. For example, Burgwal and Vieira (2014) identified a significant influence of the company size on sustainability reporting. We analyse the impact of improved human working conditions in terms of workload and costs. The company size is interpreted as the number of employees that is affected by different customer demands. The MPS is realised by a linear optimisation model and the exhaustion is integrated by a workload dependent capacity consumption.
For this, the paper is structured as follows. Section 2 presents a literature review. In section 3, the linear optimisation model is described. A test model is introduced in section 4 and the experimental design is presented in section 5. The numerical results and a discussion are outlined in section 6. The paper ends with a conclusion in section 7.

LITERATURE REVIEW

Due to exhaustion, performance deficits can be observed (Boenzi et al., 2015). For example, an increased error rate (Neumann and Dul, 2010; Yeow et al., 2014), lower productivity (Barker and Nussbaum, 2011) and decreasing motivation (Nijp et al., 2012) might occur. According to Nerdinger et al. (2014), physical diseases (e.g. musculoskeletal disorders) might occur as well. One reason for exhaustion, for example, are inadequate working conditions. In this regard, employees report, among other things, a high work intensity (DGB Index Gute Arbeit, 2014), the number of overtime hours (Ahlers, 2017) and deviations from regular working hours (Ahlers, 2017).
Exhaustion and performance deficits are not quantified for a long-term period (e.g. several years). Therefore we consider existing approaches to short-term muscle fatigue. In this context, there are methods for risk assessment of musculoskeletal disorders (e.g. OWAS, NIOSH, RULA, OCRA) to take into account the ergonomic risks of a particular task. These methods are considered, for example, to determine a maximum endurance time (MET) (e.g. Frey Law and Avin, 2010; Garg et al., 2002). In addition, an exponential increase in fatigue over time has been identified (see e.g. Ma et al., 2011).
Research on PPC has addressed this topic as follows. At the scheduling level, exhaustion is usually considered in the areas of assembly line balancing and job rotation. For

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example, the ergonomic risks are minimised in Bautista et al. (2016) and Mossa et al. (2016) and constrained in Kara et al. (2014) as well as Nanthavanij et al. (2010). A comprehensive overview is given by Otto and Battaïa (2017). In lot sizing, the already mentioned methods are used to avoid lot sizes with high ergonomic risks (e.g. Andriolo et al., 2016; Battini et al., 2017). Such considerations are also made in intra-logistics and warehouse management (Grosse et al., 2017). At the level of master production scheduling - to the best of our knowledge - there is only the work of Trost et al. (2019a), who identify the potential for improving human working conditions through an adapted MPS without increasing costs.
So far, exhaustion has not been addressed at MPS widely. Therefore, we analyse the effect of different company sizes, based on the work of Trost et al (2019a).

MODEL FORMULATION

Our model is based on the extended linear optimisation model proposed by Trost (2018), who integrate an employee workload control. We use the following notation:

Sets

$EG = \{1, \dots, EG\}$	set of employee groups, indexed by *eg*
$J = \{1, \dots, J\}$	set of production segments, indexed by *j*
$K = \{1, \dots, K\}$	set of products, indexed by *k*
$T = \{1, \dots, T\}$	set of time periods, indexed by *t*
$Z = \{0, \dots, Z\}$	set of lead-time periods for capacity load, indexed by *z*

Parameters

$Capa_{eg}$	available capacity per period and an employee of employee group *eg*
$d_{k,t}$	demand per product *k* in period *t*
$f_{z,j,k}$	capacity load factors 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 for product *k*
m_{eg}^{Cost}	cost rate for hiring an employee of employee group *eg*
n_{eg}^{Cost}	cost rate for turnover of an employee of employee group *eg*
R_j^{Max}	maximum permitted employee utilisation per production segment *j*
R_j^{Min}	minimum permitted employee utilisation per production segment *j*
$Staff_{eg}^{Cost}$	cost rate per employee of employee group *eg*
$Staff_{eg,j}^{Init}$	initial number of employees per employee group *eg* and production segment *j*
$Staff_{eg,j}^{Max}$	maximum number of employees per employee group *eg* in production segment *j*
$Staff_{eg,j}^{Min}$	minimum number of employees per employee group *eg* in production segment *j*
$Staff_j^{TotalMax}$	maximum number of employees in production segment *j*
V	number of periods for overtime balancing
we_{eg}	lead-time periods for hiring employees of employee group *eg*
wf_{eg}	lead-time periods for employee turnover of 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*
$I_{k,t}$	inventory level per product *k* in period *t*
$m_{eg,j,t}$	number of hired employees of employee group *eg* in production segment *j* and period *t*
$n_{eg,j,t}$	number of employee turnover of employee group *eg* in production segment *j* and period *t*
$overtime_{j,t}$	used overtime per production segment *j* and period *t*
$Staff_{eg,j,t}$	number of employees of employee group *eg*, production segment *j* and period *t*
$x_{k,t}$	production quantity per product *k* in period *t*

Objective Function

The objective is to minimise the total costs from inventory holding, employment as well as employee hiring and turnover (equations (1)-(6)).

$$Objective\ Function: Minimise\ (TotalCosts) \tag{1}$$

$$TotalCosts = InventoryCosts + StaffingCosts + HiringCosts + TurnoverCosts \tag{2}$$

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

$$StaffingCosts = \sum_{t=1}^{T} \sum_{j=1}^{J} \sum_{eg=1}^{EG} Staff_{eg}^{Cost} \cdot Staff_{eg,j,t} \tag{4}$$

$$HiringCosts = \sum_{t=1}^{T} \sum_{j=1}^{J} \sum_{eg=1}^{EG} m_{eg}^{Cost} \cdot m_{eg,j,t} \tag{5}$$

$$TurnoverCosts = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{eg=1}^{EG} n_{eg}^{Cost} \cdot n_{eg,j,t} \quad (6)$$

Constraints

At the constraints, there are the inventory balance sheet (equation (7)), the definition of the initial inventory level (equation (8)) and equation (9) determine the capacity requirements.

$$x_{k,t} + I_{k,t-1} - I_{k,t} = d_{k,t} \quad \forall\, 1 \le k \le K;\ \forall\, 1 \le t \le T \quad (7)$$

$$I_{k,t=0} = I_k^{Init} \quad \forall\, 1 \le k \le K \quad (8)$$

$$\sum_{z=0}^{Z}\sum_{k=1}^{K} f_{z,j,k} \cdot x_{k,t+z} = b_{j,t} \quad (9)$$
$$\forall\, 1 \le j \le J;\ \forall\, 1 \le t \le (T - Z)$$

Aspects of personnel requirements planning are considered as follows. We define the available capacity (equation (10)) and allow hiring and turnover of employees, which is integrated by the employee balance sheet (equation (11)) and the determination of the initial employee level (equation (12)). For this we distinguish between different employee groups (EG). Lead-times for hiring (we_{eg}) and turnover (wf_{eg}) are considered as well. With equation (13) and (14) we ensure that an adequate number of (skilled) employees are available and that only a limited number of employees can be employed. Equation (15) represents that the available number of skilled employees is limited on the labour market.

$$\sum_{eg=1}^{EG} Staff_{eg,j,t} \cdot Capa_{eg} = a_{j,t} \quad (10)$$
$$\forall\, 1 \le j \le J;\ \forall\, 1 \le t \le T$$

$$Staff_{eg,j,t} = Staff_{eg,j,t-1} + m_{eg,j,t-we_{eg}} - n_{eg,j,t-wf_{eg}}$$
$$\forall\, 1 \le eg \le EG;\ \forall\, 1 \le j \le J;\ \forall\, 1 \le t \le T \quad (11)$$

$$Staff_{eg,j,t=0} = Staff_{eg,j}^{Init} \quad (12)$$
$$\forall\, 1 \le eg \le EG;\ \forall\, 1 \le j \le J$$

$$Staff_{eg,j,t} \ge Staff_{eg,j}^{Min} \quad (13)$$
$$\forall\, 1 \le eg \le EG;\ \forall\, 1 \le j \le J;\ \forall\, 1 \le t \le T$$

$$\sum_{eg=1}^{EG} Staff_{eg,j,t} \le Staff_j^{TotalMax} \quad (14)$$
$$\forall\, 1 \le j \le J;\ \forall\, 1 \le t \le T$$

$$Staff_{eg,j,t} \le Staff_{eg,j}^{Max} \quad (15)$$
$$\forall\, 1 \le eg \le EG;\ \forall\, 1 \le j \le J;\ \forall\, 1 \le t \le T$$

The employee workload control is represented by equation (16) and (17). Thus, it is enabled to control the work intensity (average utilisation) as well as the deviations in regular working hours ($R_j^{Max} - R_j^{Min}$).

$$R_j^{Max} \cdot a_{j,t} \ge b_{j,t} \quad (16)$$
$$\forall\, 1 \le j \le J;\ \forall\, 1 \le t \le (T - Z)$$

$$R_j^{Min} \cdot a_{j,t} \le b_{j,t} \quad (17)$$
$$\forall\, 1 \le j \le J;\ \forall\, 1 \le t \le (T - Z)$$

Overtime can occur if the maximum utilisation (R_j^{Max}) is over 100%. We control the use of overtime by equations (18)-(20). However, overtime do not result in additional costs because they have to be compensated within a specific time interval (by equation (19)) which meets legal restrictions. When the maximum utilisation is less than 100% these constraints are not restrictive.

$$b_{j,t} - a_{j,t} = overtime_{j,t} \quad (18)$$
$$\forall\, 1 \le j \le J;\ \forall\, 1 \le t \le (T - Z)$$

$$\sum_{t'=t-V}^{t} overtime_{j,t'} \le 0 \quad (19)$$
$$\forall\, 1 \le j \le J;\ \forall\, 1 \le t \le (T - Z)$$

$$\sum_{t'=0-V}^{t=0} overtime_{j,t'} = 0 \quad \forall\, 1 \le j \le J \quad (20)$$

TEST PROBLEM

We consider an application from the railway industry in order to analyse the effects of different company sizes. Within the railway industry, there is a high human impact due to a low degree of automation (Neumann and Krippendorf, 2016). For good readability, this test problem is rather small. However, the results might not be dependent on the specific problem instance.
At first, general parameters are presented in Table 1. The different employee groups (EG) are interpreted as core employees ($eg = 1$) and temporary employees ($eg = 2$).

Table 1
General Parameters.

Parameter	Value
J	2
K	2
EG	2
Z	1

The employment of the temporary employees are outsourced to an employment agency as personnel leasing. For that reason, the costs for hiring (m_{eg}^{Cost}) and turnover (n_{eg}^{Cost}) as well as the lead-times for hiring (we_{eg}) and turnover (wf_{eg}) are higher for core employees than for temporary employees. The costs per employee of employee group and per period ($Staff_{eg}^{Cost}$) are taken from the IG Metall labour agreement for metal and electrical industries, Saxony, Germany from salary group five (additional level) (IG Metall, 2018) and 21.5% employer contribution are included as well. The staffing costs for the temporary employees are higher, due to the agency service fees of 80%. Further, it is assumed that these employees have an experience gap compared to the core employees. This is taken into account by a lower available capacity per employee ($CAPA_{eg}$). Table 2 presents the concrete values.

Table 2
Parameters for core employees ($eg = 1$) and temporary employees ($eg = 2$) (abbr.: Money Units; seconds).

Parameter	$eg = 1$	$eg = 2$
$CAPA_{eg}$	524 400 s	393 300 s
m_{eg}^{Cost}	15 000 MU	1 500 MU
n_{eg}^{Cost}	60 000 MU	100 MU
$Staff f_{eg}^{Cost}$	3 671 MU	5 435 MU
we_{eg}	3 months	1 months
wf_{eg}	3 months	0 months

Since different company sizes should be analysed, the minimum and maximum numbers of employees are set in such a way that they are not restrictive. Therefore, they are not presented.
Table 3 contains the cost rate for inventory holding and the initial inventory level.

Table 3
Parameters for inventory holding per product (K) (abbr.: Money Units; Quantity Units).

Parameter	$k = 1$	$k = 2$
h_k	115 MU	165 MU
I_k^{Init}	0 QU	0 QU

The remaining parameters: capacity load factors, demands and utilisation restrictions; are specific to our investigation and are explained in the next section.

EXPERIMENTAL DESIGN

This section explains the data for the individual experiments as well as the experiments itself. First, we determine a parameter setting so that a high work intensity, deviations in regular working time and overtime hours occur, which is described in the literature as reasons for exhaustion (see Ahlers, 2017; DGB-Index Gute Arbeit, 2014). We call it initial problem. Next, we modify the initial problem to improve the human working conditions and third, we consider different company sizes by defining a suitable customer demand.
Since the consequences of exhaustion analysed in this paper occur with a long-term overload, we consider a planning horizon of 84 months ($T = 84$). A 12-month warm up as well as run out phase are taken into account, so that the results from 60 months are analysed ($\hat{T} = 60$).

Initial problem

The employee utilisation is not further restricted. For this, the minimum utilisation is $U_j^{Min} = 0.00$ and overtime hours of 20% of the normal capacity are permitted ($U_j^{Max} = 1.20$). The overtime must be compensated by less working hours within 6 months ($V = 5$), so that in accordance with the working time law § 3 (in Germany) there are no additional costs. Table 4 presents the capacity load factors ($f_{z,j,k}$). They were set in such a way that similar to Trost et al. (2019a) a high average work intensity (average employee utilisation), high deviations from regular working time ($U_j^{Max} - U_j^{Min}$) and high overtime hours occur. Note that the capacity load occur only in lead-time period $z = 1$.

Table 4
Capacity load factors for the initial problem per product (K) and production segment (J) (abbr.: seconds).

Parameter		$j = 1$	$j = 2$
$f_{z=1,j,k}$	$k = 1$	3 867 s	13 976 s
	$k = 2$	4 092 s	10 184 s

Scenario with improved human working conditions

With the following setting, the human working conditions should be improved. Therefore, we limit the maximum utilisation to 95% ($U_j^{Max} \leq 0.95$). For a further reduction of the average workload, we reduce this maximum utilisation gradually (in steps of 5%). The deviations of the regular working time are limited to 10% ($U_j^{Max} - U_j^{Min} = 0.10$). In order to ensure that an arbitrarily low utilisation seems not to be economically, we consider a minimum utilisation of $U_j^{Min} \geq 0.65$. These lead to the following regarded utilisation intervals: 85-95%, 80-90%, 75-85%, 70-80% and 65-75%. The advantages of these improved working conditions are taken into account by adapted capacity load factors. For this, we assume an exponential decrease of capacity load with decreasing utilisation, similar to the course of muscle fatigue (see e.g. Ma et al., 2011). The new capacity load factors are based on the capacity load factors from the initial problem and both (the new and the old capacity load factors) are identical at an utilisation interval of 95-100%. The concrete values are given in Table 5.

Table 5
Capacity load factors for each utilisation interval of the scenario with improved human working conditions per product (K) and production segment (J) (abbr.: seconds).

Parameter	Utilisation		$j = 1$	$j = 2$
$f_{z=1,j,k}$	85-95%	$k = 1$	3 629 s	13 115 s
		$k = 2$	3 840 s	9 557 s
	80-90%	$k = 1$	3 405 s	12 306 s
		$k = 2$	3 603 s	8 967 s
	75-85%	$k = 1$	3 202 s	11 571 s
		$k = 2$	3 388 s	8 432 s
	70-80%	$k = 1$	3 017 s	10 902 s
		$k = 2$	3 192 s	7 944 s
	65-75%	$k = 1$	2 848 s	10 294 s
		$k = 2$	3 014 s	7 501 s

Company size

We define the company size as the number of employees (per production segment) and consider 16 different company sizes (see Table 6). Since the number of employees is a decision variable, we define the company size indirectly by the customer demand. For this, we consider that the demand is normaly distributed with a standard deviation of 5%. The mean values are defined in such a way, that with respect to the capacity load factors from the initial problem and the available capacity per employee from employee group $eg = 1$ the corresponding company sizes (i.e. required number of employees) result. In Table 6 there are the concrete values for company size and mean value of demand series.

Table 6

Company size per production segment (J) and mean values per product (K) for determining demand series.

Company size		Demand mean value	
$j = 1$	$j = 2$	$k = 1$	$k = 2$
1 /	3	68	64
5 /	15	339	320
10 /	30	678	641
20 /	60	1 356	1 282
30 /	90	2 034	1 922
40 /	120	2 712	2 563
50 /	150	3 390	3 204
75 /	225	5 085	4 806
100 /	300	6 780	6 408
150 /	450	10 171	9 611
200 /	600	13 561	12 815
300 /	900	20 341	19 223
400 /	1 200	27 122	25 630
500 /	1 500	33 902	32 038
750 /	2 250	50 853	48 057
1 000 /	3 000	67 076	64 076

For each company size, we realise 10 individual demand series. For the total costs, we calculate confidence intervals with an error probability of $1 - \alpha = 0.95$ and a normal distribution. We calculate the relative deviation of these confidence interval bounds to the mean value ($CI^{relative}$).

Each of these 4 160 individual planning problems (4 000 problems for the scenario with improved human working conditions from 25 utilisation combinations for segment 1 and 2, 16 company sizes and 10 demand series as well as 160 problems for the initial problem from 16 company sizes and 10 demand series) were solved with CPLEX from IBM-ILOG version 12.7.1 on a PC with a processor of 3.30 GHz and 192 GB of RAM.

NUMERICAL RESULTS and DISCUSSION

Of the 4 160 planning problems, 499 have such a long runtime that they are terminated after one hour. The resulting gap is on average 0.12% and on maximum 3.26% whereby 97.60% of the planning problems have a gap below 1%. The average runtime of all other planning problems is 160.65 seconds, while 92.90% have a runtime below 10 minutes and 1.23% above 50 minutes. For the total costs, the relative deviation of the confidence interval bounds to the mean value ($CI^{relative}$) are for all planning problems between 0.20% and 2.56% whereby the mean value is 0.47%. Thus, the confidence intervals are small and therefore they are not listed.

In the initial problem a high level of exhaustion should occur for all company sizes. In terms of work intensity, the average utilisation is 99.08% among all company sizes and production segments. The deviation of the regular working time (maximum amplitude of utilisation) is 16.14% on average. For example, this means a deviation of 6.13 hours for a 38-hours week. Overtime occur on average in 39.81% of periods, while the average overtime in these periods is 2.18% of the regular working time. However, exhaustion tends to be higher in smaller companies than in larger companies. This is illustrated exemplary in Figure 1 for the proportion of periods in which overtime occur in production segment 1. A comparable trend could be observed for production segment two, the average utilisation and the deviations of the regular working time.

As explained in section 'experimental design', the human working conditions from the intial problem are improved. For this, overtime is not permitted and the deviations from regular working time are limited to 10%. However, the permitted maximum amplitude of the utilisation is not

Figure 1 Proportion of periods in which overtime occur in production segment $j = 1$ and linear trend for each company size.

used to its limits. On average, the maximum utilisation amplitude is 6.74%. The work intensity is examined in the scenario with improved human working conditions by a (stepwise) reduced maximum utilisation. For the resulting utilisation intervals an average utilisation close to the upper interval bound occur.
In order to analyse these improvements, we also regard the resulting cost deviations compared to the initial problem. Figure 2 presents the range of cost deviations from all utilisation intervals in the scenario with improved human working conditions compared to the initial problem per company size. For all company sizes and production segments the lowest costs occur from the utilisation interval 75-85%. Thus, the decision on the optimal employee treatment is not dependent on the company size. However, the range of cost deviations from all utilisation intervals is higher for smaller companies. This indicates that the utilisation interval affects the total costs more in smaller companies up to a certain company size and an inadequate treatment of the employees is more disadvantageous. With a suitable utilisation, smaller companies might benefit more than larger companies. Therefore, especially smaller companies should focus on the treatment of their employees. But also for larger companies a suitable employee treatment is advantageous.

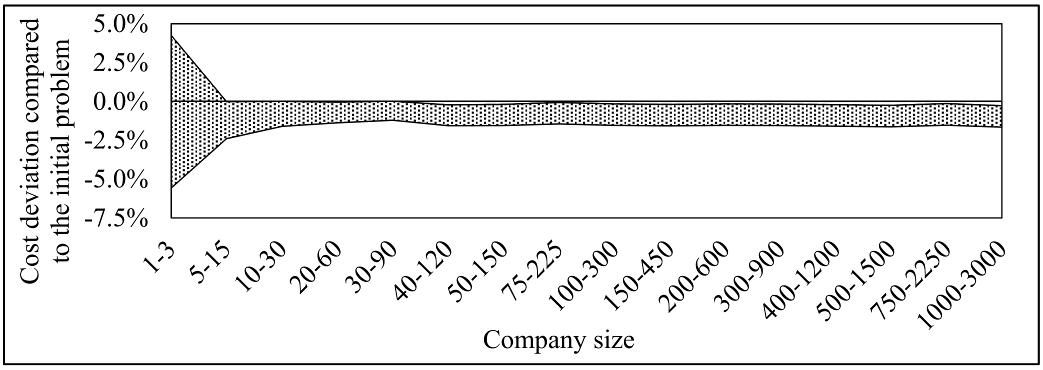

Figure 2 Range of cost deviations from all utilisation intervals per company size compared to the total costs from the initial problem.

CONCLUSION

In this paper, we adapt the MPS based on Trost (2018) by the consideration of exhaustion. We analyse its effects for different company sizes in terms of workload and costs through a sensitivity analysis. For this, we first identify exhaustion dependent performance deficits and their causes from the literature and consider the state of the art regarding the integration of exhaustion in PPC. Second the linear optimisation model for the MPS and the test problem is introduced. Thereby the exhaustion is modelled by utilisation dependent capacity load factors. The company size is interpreted as the number of employees and is defined by different normally distributed customer demands.
In the existing literature - to the best of our knowledge - there is only the work of Trost et al. (2019a), who identify the potential for improving human working conditions through an adapted MPS without necessarily increasing costs. We demonstrate that this occur independently of the company size und that the optimal utilisation is independent of the company size. According to this, the working conditions for smaller as well as for larger companies can be improved by an adapted MPS without an increase in costs. However, since in the initial problem smaller companies tend to be more exhaustive, its potential for improving working conditions is higher than in larger companies. Further the employee workload affects the total costs more in smaller companies and an adequate employee treatment is more advantageous. But also for larger companies a suitable employee treatment is recommended.
Therefore, smaller companies might benefit more from an improvement in human working conditions. The results should also affect the next two levels of PPC. This extension is intended for future research.

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