INVESTMENTS IN WORKPLACE ERGONOMICS FROM THE SUPPLY CHAIN APPROACH

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Abstract
In Europe, the number of people aged 65 and older is growing from 85 million today to more than 151 million in 2060. Therefore, the retirement age of industrial workers is rising. However, many workers are not able to work until they have reached the increased retirement age 70. Often, they are producing fewer products with lower quality. Delays and disruptions in one activity cell of a supply chain can have a ripple effect throughout the entire chain. In the article, we are investigating how investment in robots could influence Net Present Value (NPV) of a supply chain. The model is based on the Extended MRP skeleton. The investments in robots are analysed as a share of labour costs which enable decision-makers to trade-off between NPV decrease and the collaborative robots. The trade-off between higher investments in ergonomics and lower NPV is considered. Based on an Italian working environment a numerical application of the model is provided.

Keywords:
Supply chain, ergonomics, industrial workers, aging, investments, MRP, Laplace transforms.

1 INTRODUCTION

1.1 Increasing retirement age
In Europe, the number of people aged 65 or older is about to grow from 85 million today to more than 151 million in 2060 [1]. The EUROSTAT [2] estimates that in 40 years 30% of EC population will be over 65 years old. This means that the ratio of productive individuals to retired people will be 2:1 (current 4:1). Companies and societies are responding to these demographic changes by (a) adapting their production to the needs of seniors, and (b) increasing the retirement age. An aging workforce requires to integrate ideas from the field of ergonomics like [3,4], assisted working [5,6], mini- and home-manufacturing [7,8] and new work design [9] to utilize the growing number of ageing workers. An older expert is still capable to be the master craft men if better ergonomic solutions are developed and implemented. A new generation methods modelling interactions between humans and the collaborative robots will provide the well-being during working for older, highly skilled expert operators.

1.2 Workplace ergonomics
The problem of poor workplace ergonomics is a hot topic today. Ergonomic risks at the workplace cause a lot of damage to workers, and financially damaging the economy in general, like described in Otto and Scholl [10] or Battini et al. [11]. Popular assessment methods have been developed in the last decade as in the projects: RULA, OCRA checklist, REBA and OWAS, Strain Index, [12]. In the past, improvements of ergonomics were possible by implementation of modern designs of tools and working environments, comfortable and suitable for human use. Nowadays the objectives of ergonomics can be identified as the usability and safety of systems where the operator is considered as an integral part of production as written in the paper of Vignais et al [13]. Ergonomics as the theory and practices can therefore be understood as the study and design of complex systems whose effectiveness is determined by the functioning of the system and its sustainability in terms of technological, economic and social features. An increasing attention is currently paid to the interaction between human and machine within the production cycle and to the linkage between cognitive and physical aspects linked to diverse humans and diverse necessities of highly skilled workers. A large gap is present in the theory of ergonomics between analysis of physical and psychosocial factors, giving specific methods and design guidelines for elderly experts. These are critical aspects in the analysis of value chain of valuable and highly customized products as the ones considered in the present paper. In this handcrafted working environment, the human operator is highly skilled and experienced in the manual creation of the sophisticated products. As a consequence, the working environment of the future factory will take into consideration the expecting decline of functional capacities regarding ageing. Robots will become a safe help to reduce fatigue and cognitive stress during the work of older workers. To invest or not to invest in such ergonomic environment is the question to which we shall answer using the model developed here.

2 THE MODEL

2.1 Definitions and notation
The trade-off between additional pension for early retirement age is based on increased contributions $\alpha_i, c_{L,i}$ from the gross earnings which increase from $c_{L,i}$ to $c_{L,i} + \alpha_i c_{L,i}$ where $\alpha_i c_{L,i}$ is divided to the part which goes to the fund for investments in ergonomics $\alpha_i c_{L,i}$, and to the part $\alpha_i, c_{L,i}$, as the contributions from gross earnings to the extra occupational pension schemes $\alpha_i, c_{L,i}$. Thus, if the labour cost would increase from $c_{L,i}$ to $c_{L,i}(1 + \alpha_i, c_{L,i})$, where $\alpha_i, c_{L,i}$ are factored into the program of investments into ergonomics. There are two options and many combinations of decisions: the ergonomics could be improved enabling seniors to work longer or retirement age of a worker at the workplace $i$ can be lowered. Any of these decisions could increase the quality and quantity of production in the workplace and reduce the lead time in a supply chain. The benefit to the total supply chain could be evaluated through using the Net Present Value (NPV) approach only, because investments and activities have different dynamics on the time horizon of the production and distribution in total supply chain. Our analysis is based on MRP theory, as found in the papers of Grubbström [14,15] and later extended to the global supply chain by Bogataj and Bogataj [16] and Bogataj et al. [17] in which the location is also considered, including regional characteristics, such as the cost of labour. We shall use the notation as given in the Table 1.
According to the basic MRP theory [14,15] shortly described below, the j-th process is run on activity level (in node j) having intensity \( P_j \), the volume of required inputs of item \( i \) is \( h_{ij} P_j \) per unit time. The total of all inputs may then be collected into the column vector \( HP \). The net production is determined as \( (1 - H)P \). In general, \( P \) (and thereby net production or manipulation with cargo in the nodes) will be a time-varying vector-valued function. In MRP systems, lead times are essential ingredients and could be easily studied simultaneously in a total supply chain if using the Laplace Transforms methodology. The lead time of a process is the time in advance of completion or loading on trucks according to the requirements of customer. If \( P_j(t) \) is the rate of items \( j \) planned to be completed at time \( t \), then the quantity \( h_{ij} P_j(t) \) of items \( i \) need to be available for production or reloading in a time unit which is lead time \( \tau_j \) in advance of time \( t \), i.e. at time \((t - \tau_j)\). Volume \( h_{ij} P_j \) of item \( i \), previously having been part of the available inventory, at a time \((t - \tau_j)\), was earmarked for the specific production or just manipulation \( P_j(t) \) and thereby moved into work-in-process or logistic process (activities in general). At time \( t \), when this activity is completed, the identity of the type of the item \( i \) disappears and the newly produced or reloaded items appear instead. While item \( i \) is assumed to be located previously at location \( i \) it will be available for activity \( j \) at location \( j \) before activity \( P_j(t) \) starts, and it will need a certain time \( \tau_j \) to arrive there. As this basic theory was presented in many articles of Grubbström and Bogataj listed in the References, therefore we shall not go into detail here. For our needs we consider an assembly system, in which the components of process \( j \) need to be in place \( \tau_j \) time units before completion and sent from parent node \( i \) to \( j \) with an additional (transportation) time delay \( \tau_{ij} \) in advance, which will be here negligible (the activities are running very close each to other). This process can be perturbed by reducing the functional capacities of aging workers. The input requirements are given as transforms in the generalised transportation-production-input matrix, which is denoted \( H(s) \). Thus, the requirements for the production plan \( \tilde{P}(s) \) written as \( H(s)P(s) \) are specified in the frequency domain where

\[
H(s) = \begin{bmatrix}
0 & 0 & \cdots & 0 & e^{st_1} & \cdots & 0 \\
\ddots & \ddots & \ddots & \vdots & \vdots & \ddots & \vdots \\
h_{n1} & h_{n2} & \cdots & 0 & & \cdots & 0 \\
\end{bmatrix}
\]  

(1)

2.2 Perturbations of supply chain in extention of Grubbström’s Material requirements planning (MRP) model

There are some places of production \( i \) where workers work on an item longer than necessary and better ergonomic conditions are needed. This occurrence creates the additional lead time \( \Delta \tau_i \), that the total lead time in such a place is equal to \( \tau_i = \tau_i(1 + \delta_i) \). This increase can be described by \( H(s) \), in which case so that requirements for the production plans is a complex-valued function \( \tilde{P}(s) \) where the frequency variable \( s \) is from the frequency domain and \( (1) \) would be written as follows:

\[
\tilde{H}(s) = \begin{bmatrix}
0 & 0 & \cdots & 0 & e^{st_1(1+\delta_i)} & \cdots & 0 \\
\ddots & \ddots & \ddots & \vdots & \vdots & \ddots & \vdots \\
h_{n1} & h_{n2} & \cdots & 0 & & \cdots & 0 \\
\end{bmatrix}
\]  

(2)

The net production of such a system \( \tilde{x}(s) \) will conveniently be written as follows:

\[
\tilde{x}(s) = (1 - \tilde{H}(s))\tilde{P}(s)
\]  

(3)

For cyclical processes, which repeat themselves in constant time intervals \( \Gamma_j \), \( j = 1, 2, \ldots, m \), the plan \( \tilde{P}(s) \) is written as suggested by Grubbström [14,15] and Bogataj et al [17] and here extended because of ageing to the perturbed cases:

\[
\tilde{P}(s) = \tilde{\tilde{H}}(s)\tilde{\Gamma}(s)\tilde{P} = \begin{bmatrix}
\frac{-st_1(1+\sigma_i)}{e^{1-e^{-s(1+\delta_i)}}} & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & \frac{-st_1(1+\sigma_i)}{e^{1-e^{-s(1+\delta_i)}}}
\end{bmatrix} \tilde{P}
\]  

(4)

Here \( \tilde{\tilde{H}}(s)\tilde{\Gamma}(s) \) is the product of perturbed matrices.

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**Table 1. The basic notation and abbreviation.**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H )</td>
<td>Input matrix (Bill-of-Materials), describing how many items ( (\tilde{P}_{ij}) ) from activity cell ( i ) are needed to produce one item in activity cell ( j ) as a child node.</td>
</tr>
<tr>
<td>( \tilde{h}_{ij} \in H )</td>
<td>( \tilde{h}<em>{ij} ) Input matrix (Bill-of-Materials), describing how many items ( (\tilde{P}</em>{ij}) ) from activity cell ( i ) are needed to produce one item in activity cell ( j ) as a child node.</td>
</tr>
<tr>
<td>( P_j )</td>
<td>Intensity of activities in ( j )-th activity cell</td>
</tr>
<tr>
<td>( h_{ij} P_j )</td>
<td>Intensity of flow from ( i ) to ( j )</td>
</tr>
<tr>
<td>( \tau_j )</td>
<td>Lead time for the manipulation of item ( j )</td>
</tr>
<tr>
<td>( \Gamma )</td>
<td>Diagonal lead time matrix</td>
</tr>
<tr>
<td>( \mathcal{F} )</td>
<td>The Laplace (complex) frequency in the Laplace transformed frequency domain</td>
</tr>
<tr>
<td>( \mathcal{H}(s) )</td>
<td>Generalised input matrix</td>
</tr>
<tr>
<td>( \mathcal{H}(s) )</td>
<td>Generalised perturbed input matrix</td>
</tr>
<tr>
<td>( \tilde{D}_e^{out} )</td>
<td>Vector of demand dynamics</td>
</tr>
<tr>
<td>( e^{\omega t} )</td>
<td>Growth of production and demand</td>
</tr>
<tr>
<td>( \alpha_{E,J \Gamma} )</td>
<td>Contribution to the annuities for investments in ergonomics per worker per production unit</td>
</tr>
<tr>
<td>( \alpha_{J \Gamma} )</td>
<td>Contribution to the occupational pension fund per worker per production unit</td>
</tr>
<tr>
<td>( \Gamma_{J \Gamma} )</td>
<td>The length and increase of cycle in the activity cell ( i )</td>
</tr>
<tr>
<td>( \Delta \tau_{ij} )</td>
<td>Time delays in production/distribution,</td>
</tr>
<tr>
<td>( \Delta \tau_{ij} )</td>
<td>Starting time of an activity inside a cycle</td>
</tr>
<tr>
<td>( p, \Delta p )</td>
<td>Price vector ( p ) and decrease of price ( \Delta p ) per unit of item</td>
</tr>
</tbody>
</table>
\( \tilde{f}(s) \) and \( \tilde{\Gamma}(s) \), the latter, being developed as unperturbed in Grubbström [14,15] \( \dot{p} \) is a vector of constants: for instance, \( \dot{p} \) could describe the total amounts (batch sizes) to be produced in (or delivered by) each process during one of the periods \( \tau_j + \Delta \tau_j \), \( j = 1, 2, \ldots, n \). Furthermore, in the above equation (4), \( \{t_j(1 + \sigma_j) \} \), \( j = 1, 2, \ldots, n \), are the points in time when the first of each respective process cycle starts being perturbed because of declining functional capacities of workers. Please refer to the details in Grubbström [14,15] and Bogataj et al [17], where Eq. (4) is developed. We shall use now the approximation for perturbed expression describing \( \tilde{P}(s) \):

\[
\tilde{P}(s) = \tilde{f}(s) \tilde{\Gamma}(s) \dot{P} = \begin{bmatrix}
\frac{e^{-st_j(1+\sigma_j)} \hat{P}_1}{1-e^{-s(1+\Delta \tau_1)}} \\
\vdots \\
\frac{e^{-st_j(1+\sigma_j)} \hat{P}_n}{1-e^{-s(1+\Delta \tau_n)}}
\end{bmatrix}
\]

\[
\dot{P} = \begin{bmatrix}
\frac{1}{\Gamma_1 + \Delta \Gamma_1} \\
\vdots \\
\frac{1}{\Gamma_n + \Delta \Gamma_n}
\end{bmatrix}
\]

If the demand for final products in a supply chain is growing by increasing general productivity rate \( \omega \), we can write the perturbed dynamics:

\[
(I - \hat{H}(s)) e_0^\omega \begin{bmatrix}
\frac{e^{-st_j(1+\sigma_j)} \hat{P}_1}{\Gamma_1 + \Delta \Gamma_1} \\
\vdots \\
\frac{e^{-st_j(1+\sigma_j)} \hat{P}_n}{\Gamma_n + \Delta \Gamma_n}
\end{bmatrix} \dot{P} =
\]

\[
\dot{\hat{e}}(t) &= \dot{D} e^{\omega t}
\]

\[
2.3 \text{ The Net Present Value approach for evaluation of investments in ergonomic environment for the old workers}
\]

A large gap is already present in studies of ergonomics between reduced functional capacities of older worker and evaluation of investments in ergonomic support. These are critical aspects in the value chain of high value highly customized products as the ones considered in the present paper. In the handmade working environment, the worker (craft-man) has specific skills and experiences in the manual creation of the sophisticated products, and it is difficult to get a younger worker with such specific skills. The work of younger workers could give the products with lower quality and consequently even lower prices. For such a case the collaborative robots could become a safe help to reduce fatigue and cognitive stress of older worker. To invest or not to invest in such ergonomic environment for older workers is the question to which will be given the answer using the model developed here on the bases of NPV evaluation of activities and investments. During the last few years, a substantial number of new developments with respect to treating NPV in a supply chain have been reported, for instance, by Chen [18] Liu and Cruz [19], Marvin et al [20] and many others. For evaluations of activities and investments in ergonomics in our analysed production activities also the NPV criterion function will be used, as advised by Grubbström [14,15], developed further, considering also environment by Bogataj et al [17] and Bogataj, Grubbsström [21,22], and elaborated for the cases of reverse logistics in Kovačić et al [23] and Kovačić and Bogataj [24,25]. Also, softly analysed in Usenik and Bogataj [26] and Kovačić et al. [27], using fuzzy set approach.

Let us collect the economic values of items into a perturbed price vector \( p \), which is a row vector, as follows:

\[
p = p^t + \Delta p = \begin{bmatrix}
p_1(1 + \delta_1), p_2(1 + \delta_2), \ldots, p_n(1 + \delta_n)
\end{bmatrix}.
\]

where \( \delta_i \) is the relative reduction of prices of item \( i \) \((\delta_i \leq 0)\), because the worker in the production unit \( i \) is no longer able to assure the best quality of products, due to his advanced age or because we have replaced this worker with a new one without needed specific skills.

If the owners would invest in ergonomically sound conditions in their workplaces, they could influence the reduction of negative \( \delta_i \) by a certain amount. The choice between better products with higher price and reduced lead-times on one hand and decision to invest or not to invest in improvements of ergonomic conditions, on the other hand, can be achieved based on the NPV evaluation. According to the Net Present Value Theorem, the NPV of the cash flow is obtained by replacing the complex frequency \( s \) with the continuous interest rate \( \rho \) and thereby embedding the time preference of the decision maker in the model, where also the economic growth is assumed:

\[
\text{NPV}_{\text{prod}} = (p + \Delta p) x(\rho - \omega) = \sum_{i=1}^{n} \begin{bmatrix}
p_i(1 + \delta_i) \tilde{\eta}_i(\rho - \omega)
\end{bmatrix} \tilde{\eta}_i(\rho - \omega),
\]

However, the old age of industrial workers is not reflected exclusively in the quality of the product, but often also in additionally delayed timing as well as already described in (2). These issues cause also a perturbation of \( \tilde{f}(\rho) \) and \( \tilde{\Gamma}(\rho) \) as described by the equations (4) to (6) which must be considered in equation (9) for perturbed ordering as:

\[
\text{NPV}_{\text{ord}} \equiv -K \cdot \begin{bmatrix}
\frac{1}{\Gamma_1 + \Delta \Gamma_1} \\
\vdots \\
\frac{1}{\Gamma_n + \Delta \Gamma_n}
\end{bmatrix} \begin{bmatrix}
e^{-s(1+\Delta \tau_1)} \hat{P}_1 \\
\vdots \\
e^{-s(1+\Delta \tau_n)} \hat{P}_n
\end{bmatrix}^t
\]

where \( K \) is a row vector of the setup costs and other fixed costs of cycle also costs of annuities for other investments except the collaborative robots. The total NPV of all activities \( \text{NPV}_{\text{tot}} \) in case of aging without adaptation of ergonomic improvements is therefore:

\[
\text{NPV}_{\text{tot}} \equiv \frac{1}{\rho - \omega} \begin{bmatrix}
[p + \Delta p] (I - \tilde{H}(\rho - \omega)) - K
\end{bmatrix} \begin{bmatrix}
e^{-s(1+\Delta \tau_1)} \hat{P}_1 \\
\vdots \\
e^{-s(1+\Delta \tau_n)} \hat{P}_n
\end{bmatrix}^t
\]

Considering a long-term profit of a supply chain and its NPV we also need to include the direct costs of labour and investments in robots into account. The total NPV \( \text{NPV}_{\text{tot}} \) is reduced for the payments to the labour in individual places of activities with production or distribution intensity \( \hat{P}_i \), including the part of earnings which goes to the occupational pension funds, and the amount which goes to the annuity stream of investment in ergonomics to support workers, like investments in robots and other new equipment which improve ergonomics of workers. Here the investments to the robots will be considered as a part of earnings (tied to work) and not to fix costs. The early retirement age, as determined in an occupational pension scheme and trade-off between additional pension and investments in ergonomics, could be achieved by
increasing the contributions from gross earnings \( c_{L,i} \) to the extra occupational pension schemes \( \alpha_{i}, c_{L,i} \) for workers at the activity cell \( i \) and to the part of income which goes to the annuities for robots and other investments in ergonomics \( \alpha_{E}, c_{L,i} \), calculated relatively to the costs of labour. Thus, if the labour cost would increase from \( c_{L,i} \) to \( c_{L,i}(1 + \alpha_{i,j} + \alpha_{E,i}) \), where \( \alpha_{E}, c_{L,i} \) is factored into the program of robots and other investments into ergonomics, the ergonomics could be improved enabling seniors to work longer, and \( \alpha_{i,j}, c_{L,i} \) may lower the retirement age of a worker at the workplace \( i \). Any of these decisions could increase the quality and quantity of production in the workplace and reduce the lead time in a supply chain. The costs of work which include robots in the total NPV could be written as \( c_{L,i}(1 + \alpha_{i,j} + \alpha_{E,i}) R_{i} \), where \( L \) is the number of employed at \( i \). Here \( c_{L,i}, \alpha_{E,i} \) includes maintenance and depreciation costs per cycle, where \( c_{L,i}(1 + \alpha_{i,j} + \alpha_{E,i}) \) is the cost of one unit of work, which also includes the part of gross earnings \( \alpha_{i,j} \), that is sent to the occupational pension fund to retire earlier and the amount of annuity for investments into the ergonomic improvements including investments in robots. We need to write the NPV of the cost of labour and annuities for improvement of ergonomic environment as

\[
NPV(E_r) = \sum_{i=1}^{N} c_{L,i}(1 + \alpha_{i,j} + \alpha_{E,i}) L_i \rho \rho (1 - \omega) \tag{11}
\]

Therefore, the NPV of the profit of total supply chain

\[
NPV_{\text{profit}} = \left[ (p + \Delta p)(1 - \tilde{H}(\rho - \omega)) - K - L_C \right] \cdot \frac{1}{\rho - \omega} \left[ \frac{e^{(\rho - \omega) \tilde{P}_1}}{\Gamma_1 + \Delta \Gamma_1} \cdots \frac{e^{(\rho - \omega) \tilde{P}_n}}{\Gamma_n + \Delta \Gamma_n} \right]^T > 0 \tag{12}
\]

Trade-offs between \( L_a \), \( \Delta p \) and delays \( \Delta \Gamma_i \), \( \sigma_i \), and \( \Delta t_i \) should be considered. Here we wrote the row vectors:

\[
L_a = \left[ c_{L,i}(1 + \alpha_{i,j} + \alpha_{E,i}) L_i \right] \quad \text{and} \quad L_C = \left[ c_{L,i}(1 + \alpha_{i,j} + \alpha_{E,i}) L_i \right] \tag{13}
\]

\( L_a \) is the cyclical contribution to the investments in robots and other ergonomic improvements as annuities paid for these investments. This annuity stream is acceptable for the supply chain, if (a); the NPV of sum of these investments and contributions to the occupational pension fund \( NPV(E_r, r) \), as expressed in (11), is less than the difference between unperturbed (improved delays and quality) and perturbed (without improvements, suffering ageing effects) supply chain, \( \Delta NPV_{\text{tot}} \) which include production and setup costs, as described by (10); and (b): \( NPV \) of the unperturbed total supply chain including costs of labour, achieved with this investments and contributions to the pension funds is positive, if the \( NPV_{\text{profit}} \) formalised in (12) is positive. Assuming that in the case of investments in robots and other ergonomic improvements, such perturbations will not be present anymore, we can write the requirements (a) for the annuity stream of investments in ergonomics and pension fund ant their \( NPV \) as:

\[
(p - \omega) \cdot I = \frac{\sum_{i=1}^{N} e^{(\rho - \omega) \tilde{P}_i}}{\Gamma_i} \leq p \cdot (1 - \tilde{H}(\rho - \omega)) \cdot \frac{e^{(\rho - \omega) \tilde{P}_n}}{\Gamma_n} \tag{14}
\]

3 A NUMERICAL EXAMPLE

The numerical example is getting inspiration from the Italian automotive sector, from an Italian manufacturer of luxury cars. The company is a leader in the market and is distinguished for the product quality, reliability and technical excellence. The product design and production is all made in Italy and highly personalized: the car interiors are completely designed and manufactured in accordance with the specific customer requests therefore the variance of \( T \) is high. In the Saddlery area of the industrial plant a specific knowledge is available from the older human workers involved. In fact, the saddlery process adds so much value to each product by providing highly personalized vehicles’ interiors that replace them with younger workers could influence the quality of interior. A very specialized team of workers is here available providing specific knowledge in leather cutting and other activities to the final assembly. For car interiors, the company employed highly skilled and specialized operators for many processes. The manual work account about a 95% of the total work done in this division and the quality and personalization of the products are constantly monitored. All parts are manually manufactured and assembled by highly experienced elderly workers, who are involved especially in the interior design and work of highly skilled artisans. Ergonomic improvements in the saddlery department could enable these older workers to perform better and reducing the cycle time from nearly 2 hours to the norm of 1.5 hours for production of 1 cars if 2 workers are working in each of the stations 1, 2 and 4 and 4 workers at the station 3.

The investments in ergonomics including robots and their maintenance would be around 60,000 € per each collaborative robotic arm per each worker in station \( i = 2 \) and \( i = 3 \). It means all together 6 robotic arms which means around 360,000 €. By investing in a new automatic system constituted by the collaborative robots, capable to help and guide the human worker during the assembly
phase of the leather pieces on the composite parts, it could be possible to increase the overall efficiency and quality of the gluing process of the interiors (raw materials: leather and composites). The new robot will provide the needed flexibility of the interfaces between parts and workstations. The automatic system will support the correct coupling of leather and composites parts, by guiding the human operator during the process and by avoiding dangerous head/neck movements and harmful postures. From the production in line of 12 successive working stations with τ_v = 90 min we shall consider only section of 3 working stations 9-11 in the line and saddlery that supply station no 10 (in subsystem denoted 2), where highly skilled but older workers are supplying station 10 (denoted 3 in subsystem) with car seats. They have to produce pair of seats each 90 minute. But they have problems to reach the norm of 90 minutes per production of 2 seats for 1 car. There is no problem with proper timing at other 9 working stations where the norm is the same (90 minutes per car). There is not allowed to produce lower quality products. Even if we wary cost of labour between 25 and 40 EUR per hour and the investment in collaborative robots between 30.000 and 90.000 EUR the model demonstrates that investments in ergonomics in case of aging workforce increases NPV of the supply chain.

Therefore, the annuity streams of inflows for the sold cars are:

\[
(p - \omega)(I - H_r)P |_{p=0.01} = \begin{bmatrix}
1825 & 0 & 0 & 0
\end{bmatrix}^T
\]

\[
(p - \omega)(I - H_r)P |_{p=0.01} = \begin{bmatrix}
1404 & 0 & 0 & 0
\end{bmatrix}^T
\]

And annuity stream of salaries for 10 workers would be:

\[
c_1 = \left[60 \ 90 \ 60 \ 2 \ 2 \ 4 \ 2 \right] \cdot 10^3 = 7.8 \cdot 10^6 \text{€}
\]

The cost of labour here is less than 1% of difference, therefore it is advisable to organise an additional station 2 and 3 or, even better, to invest in 6 robotic arms. At \( p = 0.01 \) the investments to robotic arms of 360,000 € would require 20% depreciation costs per year and 10% of maintenance costs which presents 108,000 € of the annuity stream only, which means much less than a new group of experts, which requires also additional fix costs for equipment of additional working station. If the perturbation of lead time is decreasing for the factors presented in the table 2, the difference of net present value of these annuity streams also decreases as presented in the table. The last data in the table is the annual cost of 6 experts at the working station 2 and 3.

From the inequality (14) it follows that even investments in amount of 360,000 €, having 30% of depreciation and maintenance annuity stream (108,000 €) are negligible according to the increased inflow when time delays are reduced and also the cycle time is reduced from 1.3 to 1 day. The conclusion is valid for any reasonable interest rate. The trade-off between investments and reduction of cycle time in the activity cell 3 and 2 is always in benefit of investments in robots if \( p = 0.01 \) or higher.

### Table 2. The differences of NPV \((p - \omega = 0.01)\) at the decreased additional delays from \(y\Gamma\) to \(\Gamma\) in comparison to NPV of 6 experts and 6 robots.

<table>
<thead>
<tr>
<th>(y\Gamma) at delays</th>
<th>Differences of the NPV (y\Gamma)</th>
<th>Differences of the NPV (y\Gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[10^6 \text{€}]</td>
<td>[10^6 \text{€}]</td>
</tr>
<tr>
<td>1.3 (\Gamma)</td>
<td>99.8 (\text{€})</td>
<td>1.005 (\text{€})</td>
</tr>
<tr>
<td>1.1 (\Gamma)</td>
<td>39.3 (\text{€})</td>
<td>1.003 (\text{€})</td>
</tr>
<tr>
<td>1.05 (\Gamma)</td>
<td>20.6 (\text{€})</td>
<td>1.002 (\text{€})</td>
</tr>
<tr>
<td>1.01 (\Gamma)</td>
<td>4.3 Labour (\text{€})</td>
<td>0.78 Labour (\text{€})</td>
</tr>
<tr>
<td>Robots (\text{€})</td>
<td>0.11</td>
<td></td>
</tr>
</tbody>
</table>

Even if we wary cost of labour between 25 and 40 EUR per hour and the investment in collaborative robots between 30.000 and 90.000 EUR the model demonstrates that investments in ergonomics in case of aging workforce increases NPV of the supply chain.

### 4 CONCLUSION

As far as the authors know this is the first attempt that Extended MRP model is applied to demonstrate the necessity of investments in ergonomics for aging workers. This is only model according to knowledge of the authors. Many workers are not able to work until they have reached the increased retirement age. To solve these problems, European companies have option to invest in an ergonomic and smart improvement of the working places/processes, to provide a better working environment. In the article, we have investigated the option to invest in
robots in production of luxury cars, showing that it is excellent choice. In our case study, we did not consider the possible perturbations in delays of transportation, because the distances in our factory are very short. Here also lower prices are not allowed, which could be subject of another implementation of model.

5 REFERENCES


