

MODELLING HUMAN SATISFACTION IN AMR-ASSISTED ORDER PICKING: AN EXPERIMENTAL EXPLORATORY STUDY OF MOTIVATION-WORKLOAD TRADE-OFFS

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Human-robot Interaction, Modelling, Simulation, Satisfaction, Human-centric, Order Picking, Warehouse

ABSTRACT

Human-robot interaction in warehouse order picking is increasingly adopted in workplaces. One of the most common robotic solutions in warehouses is autonomous mobile robot (AMR). While AMRs improve efficiency and reduce physical strain, their impact on human satisfaction remains complex, involving trade-offs between motivation and workload. This paper proposes a mathematical model of human satisfaction in AMR-assisted order picking, conceptualizing satisfaction as the difference between motivational task components and perceived workload. The model is evaluated using a within-subjects experiment where participants completed order picking manually and with AMR assistance. Additionally, a simulation scenario is implemented to demonstrate how the proposed satisfaction function can be embedded into warehouse system design and evaluated under alternative AMR deployment strategies. Results demonstrate shifts in satisfaction factors across conditions and show the model's utility for understanding satisfaction outcomes under different task allocations. However, the exploratory nature of the experiment and the limited sample size, constrains the generalisability of the empirical findings and highlight the need for further validation in larger and operational warehouse settings. This study bridges subjective experience and system design, offering a tool for human-centric simulation and decision support.

INTRODUCTION

Warehouse order picking is one of the most labour-intensive and costly activities in logistics, often accounting for over half of operational costs (de Koster et al., 2007). To enhance operational efficiency and reduce physical workload on workers, industry adoption of Autonomous Mobile Robots (AMRs) has increased

rapidly (Yee Leong and Ahmad, 2024). AMRs can transport goods and guide workers, which can reshape task structures and human roles (Stefanini et al., 2025). In addition, the introduction of AMRs changes not only productivity but also psychosocial aspects of work (including autonomy, responsibility, mental load, and satisfaction) which are critical for acceptance and long-term integration of human-robot collaborative systems (Liu et al., 2026).

Despite their operational benefits, AMRs may both reduce workload and reduce perceived autonomy by constraining human decision-making (Nikolova et al., 2024). To better understand how such factors shape employee experiences, researcher evaluations often rely on descriptive statistics to examine predictors of job satisfaction (Pasparakis et al., 2023). While informative, such approaches treat satisfaction as an output variable without defining its structure in terms of task properties. This limitation challenges the integration of human experience into decision tools that guide AMR deployment.

The objective of this work is to formalise worker satisfaction in a way that links task characteristics, perceived workload, and AMR-induced changes in job design. We define worker satisfaction as a function of motivational task characteristics and perceived workload. Building on this definition, we propose a mathematical model for AMR-assisted order picking. The model is grounded in experimental data from a within-subjects comparison of manual and AMR-assisted picking. By formalising satisfaction as a computable function, the approach enables integration of subjective human experience into system-level modelling and predictive analysis for human-centric automation design. Traditional warehouse simulation studies focus on throughput, travel time, and cost (Saini et al., 2025). In addition, human-centric indicators can be considered in simulation environments (Baddam et al., 2025). The novelty of this paper lies in treating satisfaction as an endogenous variable, enabling simulation-based exploration of human-robot task allocation strategies.

LITERATURE BACKGROUND

Human-robot interaction (HRI) integrates human workers with robotic solutions to bring complementary strengths. Robots provide physical capabilities while humans offer dexterity and situational understanding (Langås et al., 2025). However, robot integration introduces challenges in workload and satisfaction outcomes. Panagou et al. (2024) highlight that robot design features (especially interface clarity and adaptability) significantly influence both performance and satisfaction in workplace HRI, emphasizing the role of system design in shaping human outcomes.

Task execution in HRI extends beyond physical ergonomics. HRI design characteristics affect mental load, trust, acceptance, and satisfaction. Systems aligned with operator preferences further improve human experience (Rieth et al., 2024). This suggests that both motivations and workload should be considered in models of human experience.

Human autonomy (i.e., the ability to make decisions and control task execution) is a key determinant of job execution (Hosseini et al., 2024). Recent studies show that preserving worker decision control enhances perceived autonomy and work meaningfulness, while workload reduction is primarily associated with task automation (Passalacqua et al., 2025). Perceived workload is particularly relevant in collaborative systems, where robot characteristics can influence human mental workload (Haney et al., 2025).

In collaborative human-robot task execution, cognitive studies show that robots can impose or relieve mental demand depending on control allocation strategies (Karakikes & Nathanael, 2023). For example, task control can influence mental workload and satisfaction in collaborative scenarios (Tausch et al., 2022). Acknowledging these dynamics is essential when modelling subjective satisfaction.

Pasparakis et al. (2023) show that introducing robots can affect job satisfaction and self-evaluations, even when autonomy is given to the robots, potentially due to reduced complexity and mental load. However, satisfaction is typically measured as a latent outcome without a specific connection to task characteristics (Irfan et al., 2025).

The motivational dimensions included in this study (autonomy, responsibility, skill variety, and perceived performance) are consistent with established job characteristic frameworks and empirical findings in human-robot collaboration research. Prior studies have shown that autonomy and task control significantly influence perceived workload and job satisfaction in collaborative environments (Rieth et al., 2024; Wang et al., 2025). Similarly, perceived physical and mental workload are core components of subjective workload assessments such as NASA-TLX (Hart & Staveland, 1988), which can be used in HRI evaluation. While additional constructs such as trust or interaction may also influence satisfaction, the present model prioritises interpretability to allow integration into simulation environments with limited parameter complexity.

While existing research identifies factors correlated with satisfaction and workload, there is a gap in the literature regarding satisfaction functions that: (i) decompose satisfaction into interpretable latent components, (ii) consider satisfaction from experimental measures, and (iii) support integration into simulation and optimisation frameworks. This paper addresses this gap by proposing a mathematical model that articulates satisfaction as a function of motivation and workload.

EXPERIMENTAL DESIGN

The study employed a controlled, within-subjects experimental design to examine how the introduction of an AMR affects human experience during order picking tasks. Twenty participants (10 female, 10 male) were recruited for the experiment. Participants were aged between 19-53 years (mean = 26,3 years). All participants reported no physical limitations affecting task execution. Moreover, participation was voluntary, and all subjects were informed about the procedure prior to the experiment.

Each participant completed two experimental conditions: a manual order picking task and an AMR-assisted order picking task. In both conditions, participants were required to pick a predefined set of items from storage locations and complete the task based on an order list. The order lists were designed based on different numbers of books and Lego pieces. The order list was delivered to participants via a mobile application built with Adalo through a wearable device attached to their arm.

In the manual condition, participants navigated the workspace independently using a trolley to collect items. In the AMR-assisted condition, participants followed an AMR that guided them through the picking locations and carried the collected items. The AMR used in the study was a MiR200 by Mobile Industrial Robots (MiR). The robot followed a provided order list and left the storage area after the completion of the order to reach a drop off point. The order of experimental conditions was counterbalanced across participants, such that some participants completed the manual condition first and others began with the AMR-assisted condition, to mitigate potential learning and fatigue effects.

Immediately after completing each condition, participants completed a post-task questionnaire designed to capture their subjective experience. Responses were collected using a seven-point Likert scale and focused on two conceptual dimensions: motivational task characteristics and perceived workload. Motivational characteristics included perceived autonomy, responsibility, task variety, and perceived performance. Perceived workload captured both physical and mental workload experienced during task execution. For motivational characteristics, higher values indicate more favourable states however, for workload factors higher values indicate greater demand (less favourable). Figure 1 shows the order picking tasks in both conditions.

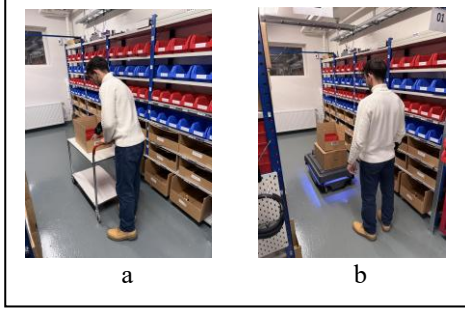


Figure 1. a. Manual Order Picking, b. AMR-Assisted Order Picking

The primary purpose of the within-subjects experiment was to generate the measures needed to instantiate the satisfaction model used in the subsequent analysis. The post-task questionnaire was deliberately aligned with the model's two components: motivational characteristics (autonomy, responsibility, skill variety, and perceived performance) and perceived workload (physical and mental workload). Collecting these measures in both the manual and AMR-assisted conditions provides comparable inputs on a common seven-point scale, enabling normalisation and direct computation of individual satisfaction scores and changes between conditions.

MATHEMATICAL MODELLING

The aim of this section is to formalise human satisfaction in order picking as a quantitative construct that can be embedded into simulation-based analysis of human-robot collaborative systems. Rather than treating satisfaction as a post-hoc descriptive outcome, the proposed model defines it as a system-level variable derived from task characteristics that are influenced by the introduction of autonomous mobile robots.

Let $i \in \{1, \dots, N\}$ index participants and let $c \in \{\text{Manual}, \text{AMR}\}$ denote the task execution condition. Human satisfaction is assumed to emerge from the interaction between two latent components: (i) motivational task characteristics and (ii) perceived workload. This assumption is consistent with established theories in work psychology and human factors, which describe job satisfaction as a balance between task execution and task demands (Genaidy et al., 2007).

For each participant and condition, a motivational component $M_i^{(c)}$ is defined as the aggregated perception of autonomy, responsibility, skill utilisation, and satisfaction with task performance. Let $q_{ik}^{(c)}$ denote the Likert-scale response of participant i to motivational question k , where $k \in \{1, 2, 3, 4\}$. Thus, the motivational component is defined as:

$$M_i^{(c)} = \frac{1}{4} \sum_{k=1}^4 q_{ik}^{(c)} \quad (1)$$

This component captures the extent to which the task supports motivation and perceived competence.

Similarly, a workload component $W_i^{(c)}$ is defined to represent the subjective demands imposed by the task. Let $q_{i5}^{(c)}$ and $q_{i6}^{(c)}$ denote the perceived physical and mental workload as response to workload questions, respectively. So, the workload component is defined as:

$$W_i^{(c)} = \frac{1}{2} (q_{i5}^{(c)} + q_{i6}^{(c)}) \quad (2)$$

Higher values of $W_i^{(c)}$ indicate greater perceived task demands.

Since questionnaire responses are measured on a discrete Likert scale, direct comparison across individuals and conditions may be affected by scale interpretation differences. To ensure comparability and support integration into simulation models, both components are normalised to the unit interval:

$$\hat{M}_i^{(c)} = \frac{M_i^{(c)} - M_{\min}}{M_{\max} - M_{\min}}, \hat{W}_i^{(c)} = \frac{W_i^{(c)} - W_{\min}}{W_{\max} - W_{\min}} \quad (3)$$

where $M_{\min}, M_{\max}, W_{\min}, W_{\max}$ correspond to the minimum and maximum possible values implied by the Likert scale.

Human satisfaction is then defined as a weighted difference between the normalised motivational and workload components. The linear formulation is intentionally adopted to preserve interpretability and enable integration into simulation environments with limited parameter complexity. While human satisfaction is inherently complex and potentially nonlinear, the aim of this model is not to fully capture all psychological dynamics but to provide a tractable and transparent representation suitable for system-level analysis.

$$S_i^{(c)} = \alpha \hat{M}_i^{(c)} - \beta \hat{W}_i^{(c)} \quad (4)$$

where $\alpha \geq 0$ and $\beta \geq 0$ are weighting parameters reflecting the relative importance of motivational benefits and workload costs. Given the exploratory nature of the study and the limited sample size, α and β are not statistically estimated but treated as design parameters. This avoids overfitting and preserves the model's suitability for simulation-based sensitivity analysis. In this study, equal weighting is assumed ($\alpha = \beta = 1$) to preserve interpretability and avoid introducing additional free parameters given the sample size. To assess the robustness of the formulation, a sensitivity analysis can be performed by varying α and β across plausible design scenarios. For example, an organisation prioritising ergonomic safety may assign a higher value to β ($\beta > \alpha$), increasing the penalty of workload in the satisfaction function. Conversely, a design strategy prioritising autonomy may assign $\alpha > \beta$. This parametric flexibility allows the model to reflect different organisational policies or worker preferences without modifying its structural form.

Equation (4) formalises satisfaction as a trade-off: satisfaction increases when motivational task

characteristics outweigh perceived workload and decreases when workload dominates. The bounded nature of the normalised components ensures that satisfaction remains within a finite interval, which is essential for numerical stability when embedding the model in simulation or optimisation frameworks. To quantify the impact of AMR assistance, the change in satisfaction for each participant is defined as:

$$\Delta S_i = S_i^{(\text{AMR})} - S_i^{(\text{Manual})} \quad (5)$$

A positive value of ΔS_i indicates that the introduction of AMR assistance improves satisfaction, while a negative value indicates a deterioration. Importantly, Equation (5) allows satisfaction effects to be evaluated at the individual level rather than relying solely on population averages.

From a modelling and simulation perspective, the proposed formulation enables human satisfaction to be treated as a variable influenced by system design choices. In a simulation of warehouse operations, the motivational component $\hat{M}$ may be linked to variables such as routing autonomy, task allocation flexibility, or human-robot task distribution, while the workload component $\hat{W}$ may be linked to walking distance, carried load, robot speed, or task complexity. As such, the model supports scenario-based evaluation of human-centric design alternatives without requiring repeated empirical studies. While human satisfaction is inherently complex, the aim of this work is not to fully capture psychological dynamics but to provide a tractable representation suitable for system-level design analysis.

EXPERIMENTAL RESULTS

This section presents and interprets the experimental results using the mathematical model of human satisfaction defined in previous section. Rather than analysing individual questionnaire items in isolation, results are structured around the motivational component M , the workload component W , and the resulting satisfaction function S . This model-based approach allows subjective experience to be interpreted as a system-level outcome of task design and AMR integration.

Table 1 shows the median and mean responses for each questionnaire item under manual and AMR-assisted order picking. Values are reported on the original seven-point Likert scale. For Motivation (q_1 - q_4), higher values indicate more favourable states; for Workload (q_5 and q_6), higher values indicate greater demand (less favourable). While mean values are reported to support aggregation into the mathematical model, Likert-scale responses are ordinal in nature. Likert items are ordinal; medians are therefore reported alongside means used for aggregation.

Table 1: Median and Mean Questionnaire Responses Across Experimental Conditions

Dimension	Questions	Manual		AMR-Assisted	
		Median	Mean	Median	Mean
Motivation	q_1	5,50	5,50	3	3,80
	q_2	6,50	6,15	3	3,90
	q_3	5,00	4,40	3	2,75
	q_4	6,00	5,30	6	5,35
Workload	q_5	4,00	4,00	2	2,40
	q_6	4,00	4,15	3	2,65

The introduction of AMR assistance leads to a clear reduction in perceived physical and mental workload. At the same time, perceived autonomy, responsibility, and skill utilisation decrease. Satisfaction with task performance remains largely unchanged across conditions, suggesting that participants felt equally capable of completing the task despite differences in task structure. A paired Wilcoxon signed-rank test (Wilcoxon, 1945) supports the item-level differences: autonomy ($p=0,0127$), responsibility ($p=0,0005$), skill variety ($p=0,0029$), physical workload ($p=0,0009$), and mental workload ($p=0,0019$) change significantly, while perceived performance does not ($p=0,9364$). These findings support the presence of a trade-off between reduced workload and reduced motivational task characteristics under AMR assistance; however, results should be interpreted cautiously given the small sample size.

Using Equations (1) to (3), motivational and workload components were computed for each participant and condition. Table 2 summarises the resulting component means and the derived satisfaction scores. Higher $\hat{M}$ shows more favourable motivational state while higher $\hat{W}$ indicates greater workload (less favourable). So higher S denotes a more favourable balance.

Table 2: Model-Based Component Values and Satisfaction Scores

Condition	M	W	$\hat{M}$	$\hat{W}$	S
Manual	5,34	4,08	0,723	0,513	0,210
AMR	3,95	2,53	0,492	0,254	0,238

The AMR-assisted condition exhibits a substantially lower motivational component and a substantially lower workload component. When combined through the satisfaction function (Equation 4), the net effect is a slight increase in overall satisfaction relative to manual order picking.

This result highlights the core insight of the proposed model: human satisfaction in collaborative systems emerges from a balance between task enrichment and task demands. While AMR assistance constrains autonomy and responsibility, the associated reduction in physical and mental workload compensates for this loss, resulting in comparable or improved satisfaction outcomes.

To further examine individual responses, the change in satisfaction ΔS_i was computed for each participant using Equation (5). Although the mean satisfaction increased under AMR assistance, individual responses varied. Inspection of individual ΔS values shows a heterogeneous distribution, with both positive and negative changes observed across participants. This heterogeneity underscores the importance of individual-level modelling and cannot be captured by average questionnaire scores alone.

From a modelling and simulation perspective, these results demonstrate that the proposed formulation behaves consistently with established human factors theory while remaining computationally tractable. The satisfaction function can be directly embedded into agent-based or discrete-event simulation models of warehouse operations, enabling designers to evaluate human-centric outcomes alongside productivity metrics when exploring alternative AMR deployment strategies.

SIMULATION-BASED PARAMETRIC ANALYSIS

This section explains a simulation-based parametric analysis which applies the proposed satisfaction model as a decision-support tool for human-centric warehouse design. By varying automation intensity and organisational priorities, it enables early-stage design-space exploration, sensitivity and robustness checks, and the identification of operating regions where predicted satisfaction is maintained or improved relative to a manual baseline. The analysis is illustrative under stated assumptions and parameter choices; the same workflow can be recalibrated with larger samples or operational data to guide iterative, evidence-informed deployment. The objective is not to simulate detailed robot motion, but to demonstrate how satisfaction can be embedded as an endogenous variable in system-level design exploration.

Let $d \in [0,1]$; denote the degree of automation, where:

$d = 0$ represents fully manual order picking,
 $d = 0,5$ represents moderate order picking, and
 $d = 1$ represents fully robot-guided order picking.

Intermediate values represent partial automation or shared control between human and robot.

The empirical results from the manual condition provide baseline values:

$$\begin{aligned}\hat{M}_{\text{manual}} &= 0,723 \\ \hat{W}_{\text{manual}} &= 0,513\end{aligned}$$

These serve as reference points for the simulation.

To model how automation affects human experience, the following structural assumptions are introduced: (i) increasing automation reduces perceived autonomy and responsibility, (ii) increasing automation reduces perceived physical and mental workload, and (iii) the effects are assumed linear for demonstrative purposes. While linear relationships are assumed for interpretability, alternative nonlinear formulations may better capture adaptation effects and will be explored in future work.

The motivational and workload components are therefore defined as functions of automation level d :

$$\hat{M}(d) = \hat{M}_{\text{manual}}(1 - \delta d) \quad (6)$$

$$\hat{W}(d) = \hat{W}_{\text{manual}}(1 - \gamma d) \quad (7)$$

where:

$\delta \in (0,1)$ is the autonomy reduction coefficient,

$\gamma \in (0,1)$ is the workload reduction coefficient.

For illustration, the following scenario parameters are adopted to explore design sensitivity; however, they are not estimated from the experiment:

$$\begin{aligned}\delta &= 0,4 \\ \gamma &= 0,6\end{aligned}$$

These values are assumed parameters selected to reflect the qualitative trend observed in the experimental results, where workload reduction is more pronounced than the reduction in motivational characteristics. They are not statistically estimated but serve as illustrative design variables within the simulation.

Satisfaction is computed using Equation (4) with equal weighting:

$$\alpha = \beta = 1$$

thus,

$$S(d) = \hat{M}(d) - \hat{W}(d) \quad (8)$$

It should be mentioned that in equation 8 the relationship between d and S is entirely mediated by the assumed functional relationships $\hat{M}(d)$ and $\hat{W}(d)$ and on weights (α, β) ; different functional forms or weights can yield different $S(d)$.

Table 3 presents the resulting values for three representative automation levels as different scenarios: manual ($d = 0$), moderate automation ($d = 0,5$), and high automation ($d = 1$). It should be mentioned that parametric analysis serves as an example of how the satisfaction function can be embedded in simulation; it is not meant as evidence that higher automation increases satisfaction.

Table 3: Parametric Simulation Results Across Automation Levels

Scenario	d	$\hat{M}(d)$	$\hat{W}(d)$	$S(d)$
Manual	0	0,723	0,513	0,210
Moderate Automation	0,5	0,578	0,359	0,219
High Automation	1,0	0,492	0,254	0,238

The results indicate that under the specific parameterisation adopted here ($\delta = 0,4$, $\gamma = 0,6$, $\alpha = \beta = 1$), while motivational characteristics decrease as automation increases, workload decreases at a steeper rate. As a consequence, overall satisfaction increases slightly with higher levels of automation under the equal-weight assumption. Importantly, this analysis is scenario-dependent and does not introduce new empirical data; rather, it demonstrates how the proposed

mathematical model can be embedded into simulation-based design exploration. By allowing automation intensity to vary continuously, system designers can predict satisfaction outcomes for intermediate task allocation strategies without conducting additional human-subject experiments.

CONCLUSION AND FUTURE WORK

This paper proposed a mathematical model of human satisfaction in AMR-assisted order picking, framing satisfaction as a computable balance between motivational task characteristics and perceived workload. Unlike conventional empirical approaches that treat satisfaction as a descriptive outcome variable, the proposed formulation defines satisfaction as a system-level quantity derived from task design properties influenced by automation.

The model was evaluated using data from a within-subjects experiment comparing manual and AMR-assisted order picking. Results showed that AMR assistance reduces perceived physical and mental workload while simultaneously reducing perceived autonomy and responsibility. When combined through the proposed satisfaction function, these competing effects resulted in comparable or slightly improved satisfaction outcomes under AMR assistance. This finding explains why automation can be simultaneously beneficial and challenging from the worker's perspective. It should be mentioned that any apparent increase in satisfaction with higher automation in our simulation is scenario-specific to the adopted parameterisation and should not be generalized without empirical consideration.

The primary contribution of this work lies in enabling satisfaction to be treated as an endogenous variable in modelling and simulation studies of human-robot collaborative systems. By linking motivational and workload components to controllable system parameters, the model supports predictive evaluation of human-centric design alternatives without requiring repeated human-subject experiments.

The current study represents an initial validation of the modelling approach. Given the small sample size and controlled experimental setting, the findings should not be interpreted as generalisable but rather as indicative of the proposed model's potential and equal weighting of motivational and workload components was assumed due to the exploratory nature of the study. In addition, the current formulation relies on self-reported Likert-scale measures and assumes linear relationships between automation intensity and human experience, which may not fully capture dynamic or nonlinear adaptation effects in real warehouse environments. Future work will investigate data-driven estimation of weighting parameters, integration of objective workload measures, and longitudinal analysis of satisfaction as workers adapt to AMR-assisted workflows. Additionally, embedding the model within full-scale warehouse simulations will enable joint optimisation of efficiency, ergonomics, and human satisfaction.

Overall, this research contributes to the modelling and simulation literature by providing a formal, interpretable, and computationally efficient representation of human satisfaction in collaborative robotic systems, supporting the design of more sustainable and human-centric automation.

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